THESIS

ENERGY CONSUMPTION IN THE USE PHASE OF RESIDENTIAL HOUSING: A CASE STUDY OF RAMMED EARTH AND WOOD FRAMED CONSTRUCTION IN THE NORTHERN COLORADO FRONT RANGE

Submitted by

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ABSTRACT

ENERGY CONSUMPTION IN THE USE PHASE OF RESIDENTIAL HOUSING:

A CASE STUDY OF RAMMED EARTH AND WOOD FRAMED

CONSTRUCTION IN THE NORTHERN COLORADO FRONT RANGE

This study investigated rammed earth (RE) housing energy consumption compared to the traditional wood frame structure (SB) typically used in residential construction in the northern Colorado Front Range (NoCOFR). There has not been a great deal of study of rammed earth and the relationship of energy consumption. Therefore, similar studies using direct observations and others using artificial neural networks (ANN) and computer statistical simulations have been used for comparing the results of this study as a validation. The objectives of this research were to evaluate the energy consumption used by both RE & SB during the use phase of the structure. While total energy use is important, this study focused on heating and cooling measured by data gathered from participant utility records. The claims, by proponents of rammed earth housing are that the inhabitants can save between 30-50% on energy consumption. The results of this focused study indicate that the energy consumption comparison is inconclusive given the limited number of rammed earth homes in the study due to the regional focus. However, as a result of this study and the communications between the researcher and the participants, it is clear that most people do not understand how their home functions. This highlights a need for further studies into how to continually educate homeowners about

home system construction and the impacts construction type has on efficient operation of heating and cooling systems.

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To my very understanding wife, Christy, my children, my parents and friends, I wish to convey my utmost thanks for their unending support and encouragement throughout this experience. I also appreciate and want to publicly thank those listed above and others that were called upon to read, review and provide tireless critiques and edits. I would like to thank my committee members, some of which went above and beyond the call to help me get this work to a state of completion. I would also like the express my gratitude for those researchers that precede me in this fascinating subject.

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CHAPTER ONE: INTRODUCTION

Throughout time, human beings created shelters using materials that were readily available and easy to manipulate. These materials typically included stone, earth, and wood. Although each of these materials is still in use today, Bourdon reminds us that, humans have utilized earth, sticks and stone as basic building materials for the better part of our existence (1995). Of these materials, earthen construction has stood the test of time being referred to as an age-old technique that utilizes only dirt to create thick, durable walls, which can be load-bearing, low cost, heat storing, and are recyclable (Wojciechowska, 2001). An individual's house is not only created to provide shelter, warmth and protection from the environmental elements (its major function) it also symbolizes a home when used as an abode (Conway & Roenisch, 1994).

This case study will compare two residential building methods: traditional stick building (SB) and rammed earth (RE) construction. The sustainability of RE is not only in material consumption, but also in the economical, efficient and effective use of resources. On specific interest in this study are the energy consumption of the residents and storage capacity of the earthen walls during the use phase of residential structures. According to the Civano study, estimates suggest that RE structures consume 30-50% less energy in some cases than similar SB houses (Chalfoun & Michal, 2003). This may be attributed to better thermal properties of raw earth and their greater wall mass and thermal inertia (Krnjetin & Folic′, 2002).

This revolutionary idea of constructing a home with the comfort of the earth has been in testing for thousands of years. Archeological remains referred to by Impson indicate the residences of the Romans in Tunisia were below ground and around a courtyard to protect themselves from the searing heat (1992).

Since the development of RE walls, many other methods of construction have been created: where available; the creation of mud bricks (adobe) and, of course, in heavily forested areas of the world the preference is wood. In stark contrast to RE, wooden SB houses were popularized in Western cultures. These structures have a recorded history of about 300 years. As societies evolve in a continuum, their expertise and use of indigenous materials provide their housing. Many of these cultures continue their reliance on materials and methods of the past. Often these regions of the world are where the forests have been depleted or the use of wood is impractical. These situations necessitate the use of traditional home building mores. The vernacular architecture which ascribes to a particular concept and its own aesthetics was not necessarily designed or built by professionals (Conway & Roenisch, 1994). The expertise learned was by contact with the existing construction methods (Sutton, 1999). The planet is replete with countries having little or no industrialized means, and therefore the earth remains the staple building material. These international communities are dependent on the use of what is locally available for building materials, and knowledge in the trades of building. These traditional building materials and techniques perfected over generations are expertly used and provide architectural quality. These structures tend to make the utmost of the manpower and natural resources available (tve.org, retrieved 2008).

This research study reviewed the background of RE and evaluated modern RE structures for its energy efficiency and energy consumption in comparison to modern SB residential structures; the chosen structures are located in northern Colorado near Fort Collins & Greeley, Colorado. The premise of this research was based on the RE residential construction in the northern Colorado Front Range (referred to as NoCOFR throughout the paper), a temperate climate and a sampling of SB residential housing. An analysis of the energy consumed in the use phase of each type of structure was preformed. The purpose of the literary review is to ensue with a critical look at RE and SB building methods from both a historical vantage of a global view, narrowing to the United States and culminating with a discourse concentrating on the projects located within the Front Range region. The antecedent evidence has established the durability and enduring nature of RE construction. Multiple virtues have been purported of earthen building material, these include high thermal mass, hygroscopicity, permeability which suggests a healthier interior environment, and a more simple low-energy building construction method (Hunting, 2003). The environmental aspects of the material properties of earth are readily apparent, yet the lingering effects (greenhouse gas emissions currently in significant debate) have been scantily examined, specifically, in the NoCOFR.

Background

Earthen structures dot the globe; these include RE, adobe, and "earthships" (earth packed into used automobile tires) to name a few typical methods of construction. David Easton suggests that historians of earthen architecture are careful to make the distinction between "raw" [which this study is concerned with] and "cooked" or baked earth (1982).

These earthen houses are constructed of the very soil surrounding the construction site, often built of the excavated soil. RE construction is utilized worldwide due to the fact that soil is readily available, it is a relatively inexpensive building material, and the labors to produce these edifices are readily available. It is claimed that the inhabitants of these homes are more amalgamated with their environment and with the mother earth upon which they rest. The charm or attraction of earthen architecture is the inherent connection to the environment (Wojciechowska, 2001).

A discussion of the constructional modalities of platform framing in contrast to rammed earth construction will supervene. Wood-framed housing (SB) typically used in the United States is based on the platform method of construction. The building is supported with some type of foundation, usually concrete poured into a removable form to create a basement, crawl space or slab on grade. This foundation is structural to carry the weight of loads bearing down, the uplift of the earth, and to minimize the lateral pressures on the building. The foundation also raises the wooden structure out of the earth above the final grade; standard construction practice, based on locally adopted code, is a minimum of 6" exposed foundation, enough to deter the moisture in the ground from wicking into the wood. Any wood that comes in contact with the foundation (concrete) needs to be chemically treated or naturally decay resistant to deter moisture absorption and decay and in some areas of the country resist termite infestation. After the foundation; the wood frame wall system is constructed. The spacing between these studs is determined by local and national building codes and the rough framing is usually inspected prior to finishes. The cavity created between these studs is filled with an insulation material; sheathing and a moisture barrier are placed on the outside and then is covered with a moisture barrier on the warm side of the wall before the finish system is installed and the interior usually has a vapor retarder and an interior finish system. The construction method of SB housing uses a wooden wall system. This system consists of more than dimensional lumber. It also includes the use of plywood or Oriented Strand Board (OSB) as well as insulation and a finished material. Typical wood framed wall systems are 4 ½" to 6 ½" in thickness.

A study based in Arizona by Candice Gossen in 1993 suggested that a prototype structure of an average 1,500 SF house consumes 14,307.6 BF (board feet) of lumber just in the walls and roof. After construction of the wood frame house is completed, the structure would consume approximately 12,236 kWh annually or 125,284,404 Btu of energy which equals nearly 5.67 ton of coal every year. This same study made the comparison of both adobe and RE prototypes which used 1,900 BF just for the roof framing (Gossen, 1993).

RE, on the other hand, uses a wider wall due to the material properties and the construction process. The procedures to produce rammed earthen walls are in direct contrast to platform construction. Traditional SB construction is piece by piece, whereas RE is a mixture of earth and water, then compressed. Similarly, both construction methods use a foundation for stability, to raise the wall above the final grade and, to ensure dryness of the wall assemblies from wicking moisture out of the ground. The problems encountered with pests commonly associated with the wooden walls are not an issue with earthen structures since there is no food source present.

A temporary form (Fig 1.0) like those used for placing concrete to form foundation walls is used to contain the soil mixture under compaction. Re-enforcement (rebar) is commonly placed in the material, similar to concrete construction practices. The compacted wall material is allowed to set and becomes a wall of 18”- 24” in measured width. The mass created is significantly denser than that of wood, brick, and even concrete block methods of fabrication.

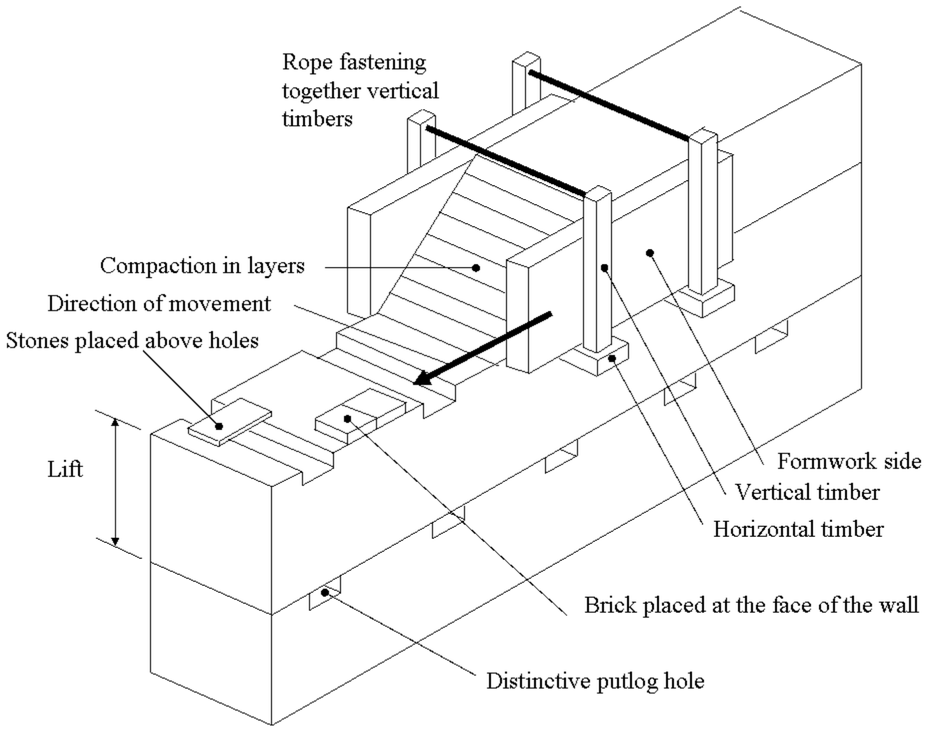

Figure 1.0 Form for Ramming Earth Graphic by historicrammedearth.wordpress.com (2008)

Purpose of the Research

Numerous RE buildings are still in existence today and are being used as housing in many parts of the world. It is important to understand why these structures are so durable and widely used. This research looked into two main elements of RE structures: 1. the significance of the RE construction methods in a historical timeframe and, 2. the energy efficiency of these structures and potential environmental impacts. The research further studied the energy consumption of this housing type.

Of particular relevance to this study is RE housing in the NoCOFR. Historical examples of RE structures in this area can be found at Fort Vazquez, Platteville, CO, and just north of Colorado at Fort Laramie, Wyoming.

Problem Statement

In most industrialized nations, RE is not considered a standard building material. Although RE is gaining acceptance in some industrialized nations; (Australia, New Zealand, France and increasingly in the southwestern United States), there continues to be a lack of general approval of earthen structures. However, increasing public awareness of the environment and current global economic woes may be the needed catalyst for increased resource conservation and stewardship of the planet. This transference of attention has motivated some practitioners to construct more environmentally-responsible houses. Hassan Fathy has summed up this thought; "while change is a condition of life, it is not ethically neutral. Change that is not for the better is change for the worse, and we must continually judge its direction," (1986, p xxii). These changing perspectives are the basis for the g*reen* or *sustainable* construction protocols that are challenging the customary housing industry. If successfully implemented, these changes in building protocol may stimulate resurgence in RE construction.

Earthen structures have been built using both raw and cooked methods. This study focused on the raw method for its perceived lower embodied energy content, availability, ease of construction, and maintenance. The prevailing claim of RE proponents is that the energy efficiency during the use phase of the residency is 50% less than those of SB construction. In an effort to validate- such claims, this research analyzed the energy use of RE and conventional SB residential construction built in the NoCOFR in the United States.

Definition of Terms

Rammed Earth

The process which a soil mixture sand, silt and clay are compacted (stuffed or packed) into a wooden form similar to concrete forms to create walls for buildings. In more modern times the ramming is done with a mechanical devise, to increase the speed of the process and to alleviate the need for intense manual labor.

Pisé

Pisé is a French word derived from the Latin verb, pinsare, the action of ramming earth. The French term pisé de terre, means compressed earth, and was first coined by Francois Cointeraux who established the *School of Agritecture* in 1791, (Lee, 2007). The term P.I.S.E. most recently has evolved into pneumatically impacted stabilized earth referred to by David Easton in his book, *The Rammed Earth Experience*, 1982.

Pisé and adobe are unfired earth construction techniques while brick and tile would be considered fired or cooked.

Biotecture

Biotecture is the use of natural building materials. These designs are created following designs of nature.

Geotecture

Earthen built architecture. This includes the processes of rammed earth, earthships (ramming earth into used automobile tires, stacked similar to laying brick and coating them with plaster, concrete, etc.), adobe, earthbags (tubes made of natural fibers filled with soil), waddle and daub (a frame of sticks or grass infilled with mud, cob (rounded balls of mud, pressed into a framework of lathe, twigs, grasses, bamboo, etc.), Stranglhem; extruded loam profiles and stacked similar to logs (Minke, 2000).

Embodied Energy

Embodied energy is the energy consumed in the process of creating and developing a product. An accounting method which determined the total energy expended for a product in the beginning of its lifecycle.

Research Question

How does the energy consumption in rammed earth (RE) residences, located within the NoCOFR region of the United States, compare with similarly located wood framed houses (SB)?

Delimitations

The NoCOFR was chosen for its shared history of settler origin, construction methods, climate, terrain, and vegetation. The NoCOFR as defined in this study is delimited to the area east of the Rocky Mountains and north of Denver and includes the cities of Fort Collins and Greeley, Colorado. The sample of houses is very selective, due to the small number of RE structures known to exist in this region. Housing units built from the 1950's until the present were the focus of this study. Even though the number of RE homes is small, they have been occupied for many years and the energy consumption data is used for comparison to SB homes of the same period and size. The framework of this research was to explore energy consumption in one phase of the building life cycle; the use phase, which is the period of occupancy of the dwelling.

This study further delimits any consideration of the economic conditions at the time of construction, quality of materials and construction, and site orientation.

Limitations

This study is limited by the potential number of RE homes identified in the NoCOFR (*see delimitations*) and the willingness of the participants (residential home owners), to extend permission to collect the necessary utility usage data for analysis.

Due to the limited number of RE homes in this area, extrapolating figures from data collected in global studies of regions with similar climates and construction methods is used to help understand the RE structure better. There are numerous examples of RE projects located in similar more moderate climes, specifically in the southwest region of the U.S. (Arizona and New Mexico). The style of construction, building material quality, and economics were not a concern of this study.

Researcher's Perspective

After my many years of practice as a Landscape Architect, I am intrigued with the literal creation of architectural structures burgeoning from the earth. I first considered underground housing as an option to explore and then became fascinated with using earth as the structure. This investigation was encouraged by a professor, an architect, in my graduate studies who suggested I pursue the study of earthen structures.

Housing made of earth is not typically a topic of general discussion. Until the 1970's, there was limited published research. It wasn't until the past few decades with the appearance of natural disasters, calamity, resource depletion, and manufactured product shortages that an environmentally focused movement allowed alternative construction methods to be seriously considered.

Can these architectural anomalies be equal or superior to the contemporary building methods of the Western United States or the industrialized nations? If this question can be answered in the affirmative, why are there not more homes constructed of rammed earth and increase in popularity as an alternative construction practice? Builders using strawbale, papercrete, and various non-stick frame construction methods are gaining a level of acknowledgement. Why not so with earthen structures?

It has been said that in comparing modern architectural practices with vernacular architecture; "the lesser the challenge for man to imprint his genius, the less artistic the product," (Fathy, 1986, preface p xix). Fathy indicates that all the advancements in technology, which appear to be progressing “towards man’s mastery of his environment,” are ideals continually being grounded to earth by the “gravitational force of human nature,” (Fathy, 1986, p xxi).

The beginning of a new century has spurred a renewed determination, a grounding of sorts, to live more responsibly among the earth’s population. The mode of rammed earth construction is being revitalized in some locales with a new vigor. Architecture involves not only function or an aesthetic appeal; it is concerned with economics, cultures and politics as well. For the purposes of this body of work, economics, specifically, the judicious usage of energy, in rammed earth compared with stick built residences is the premise of the thesis.

CHAPTER TWO: LITERATURE REVIEW

A Brief History of Rammed Earth

In the twenty-first century, amid all the technological advances circling the globe, one-third of the earth's human inhabitants continue to build their homes from earth (Easton, 1982; Jaquin, 2007). Most industrialized countries have discarded the concept of living in what is considered to be an alternative, antiquated construction method for a more mainstream, culturally-acceptable modern structure. With the modernization of the planet and the advancements in technology people are losing the attachment they once had to the earth.

This chapter provides a historical perspective of RE by tracing the usage of RE from its apparent beginnings in the city of Jericho and the Middle East to the current uses in the NoCOFR of the United States, culminating in Colorado.

The bulk of this chapter concentrates on the method of compacting soil into temporary wooden forms designed similar to today's concrete formwork. In modern applications, a binder is often added to the earth mix and steel rebar is used for structural reinforcing. Historically, this operation was performed by layering a soil recipe combined with water in a wooden formwork and tamping with stones, heavy wooden tools or simply the weight of the soil itself. The soil was allowed to dry and the forms removed. This simple yet labor-intensive method created an earthen unbaked structural shelter.

These walls, if left exposed to view, reveal the stratification pattern created by different soil mixtures being rammed together. The surface of the wall can be carved, sculpted or covered with an earthen plaster while still damp (solidearth.co.nz, 2007).

The ancient technique of ramming earth (pise´ de terre), has been dated to at least 7000 BC in Pakistan [and further back to approximately 10,000 years in Jericho] (Easton, 1982; Bourdon, 1995). It is a traditional construction method used in many applications around the world. There have been buildings as tall as seven stories high (Germany and Yemen), although most rammed earth buildings today are single- or two-stories. In Australia, a five-story hotel, The Kooralbyn Hotel Resort on Australia's Gold Coast created by architect David Oliver, has recently been built (solidearth.co.nz, 2007).

Why use the earth as shelter? Since the recorded history of mankind there has been a kinship between people and the earth. Most likely this bonding was due to the fact the earth was the source of food, water and protection from the elements. From the inception of covering oneself from weather and possible dangers, mankind has used the earth in one form or another for sustenance, protection and as a construction material.

Historical Perspective

Historical evidence indicates that the method of ramming earth for construction has been used for centuries, possibly dating back to prehistory and the Neolithic period (Brown & Clifton, 1978). In his book, *The Rammed Earth House*, David Easton, advocates that the beginnings or roots of rammed earth can be traced to the earliest settlements in the history of civilization (1982). Research indicates that the earth is a simple, solid, and proven building solution. It is estimated that this building methodology has been in use for some 10,000 years (Easton, 1982). Rammed earthen walls have been found in the city of Jericho. Easton postulates that rammed earth buildings have been located in every continent with the exception of the Arctic and Antarctic. Being very versatile, earthen construction has been used historically and continues to be used in the tropics, in the desert, in mountains, and in extreme conditions of hot, humid, and cold regions of the world.

Walter Shearer's foreword in *Natural Energy &Vernacular Architecture* by the famous Egyptian architect Hassan Fathy indicates that when looking back at history, most cultures and societies have developed or derived at least a level of sophistication for their time, greatly surpassing their contemporaries, many of which have become the new industrialized societies of today, (1986).

The interaction of cultures by migration, conquest, casual contact or trade facilitated the assimilation of the cultural traditions of others. Housing architecture, sources of food, and warfare stratagems have circumnavigated the globe by these cultural exchanges.

The recorded history of the RE as a construction method began in the Middle East and then spread eastward and westward from this epicenter. From there, this building methodology migrated to India over the Indian Ocean to Madagascar, crossing the continent of Africa to Morocco where Hannibal continued the spread by his conquests in Spain (Pliny, 1927 translation date). The Pyrenees Mountains today still proudly bear Hannibal's watchtowers. The RE technique is found across the Alps into Italy and was introduced in about 218-201 BC by Hannibal who brought this method to the Romans.

According to the writings of Pliny the Elder, a noted historian, the Romans transported the idea to France and onto the modern territory of Europe (Pliny, 1927 translation date).

Orient- Middle East- South America

The historical journey of RE begins in Jericho then spreads throughout the Middle East and South America.

Jericho

The oldest surviving continuously inhabited city in the world is claimed to be the city of Jericho (Nuttgens, 1983; Trachlenberg & Hyman, 2002; Hall, 2006). This Biblical "urban area" located in a treeless desert was constructed with the only available local resources: earth, sand and minimal amounts of water. Stones, with earth as a binding agent were used to protect the inhabitants from the searing heat of the day and frigid nighttime temperatures. The method of packing earthen walls for housing and shops is still being used in this region today. Although the use of soil as a building material was started earlier, the environmental utility of reducing the dramatic temperature swings became apparent as a positive attribute of earthen structures. The principle of compressing earth into wide walls creates what is known as the "flywheel effect." The flywheel is when the heat of the sun warms the exterior of the earthen wall and permeates inward. The heat usually takes most of the day (time lag) to penetrate the wall into the interior. By the time the heat reaches inside the house, the sun is setting and the heat is dissipated into the house at night to provide a comfortably warm ambient temperature for the occupants. The opposite effect of coolness pervades during the heat of the day, thus the circular thermal fly-wheel concept (Minke, 2000; Fathy, 1986).

Babylon

From Jericho, these techniques spread throughout the Middle East. The practice of RE was introduced into Babylon in roughly 5000 B.C. The hanging gardens of Babylon were constructed at least partially of earth. In his book *Designing the Earth*, David Bourdon claims that a portion of the palace walls in Babylon, as well as its famed Ishtar Gate were constructed of and embellished with a molded earth relief (1995, p16 side note).

Egypt

The fertile Nile region of Egypt was populated by mud brick structures similar to RE. Water, sand, and clay soils one of the quality building materials to the region, are abundant along the Nile. The periodic flooding of the river tends to establish a greater expanse of this resource, homogenous clay, which becomes very hard when dry and is used by the masses in contemporary architecture. The Egyptians commonly used a traditional process of forming bricks and then used them in adobe construction. On occasion, a mud plaster coat is applied to the exterior of the adobe brick. An example of this type of construction is Luxor from the time period 1260 BC; it is constructed of RE (Bourdon, 1995).

Central and South America- Mesoamerica

The Olmec culture around 1200 BC., settled in what we now call Central and South America (Mesoamerica) and created RE structures similar in design and appearance to those in the Middle East.

After approximately 1000 AD, archaeological evidence suggests that RE techniques were then used for massive fortification. Large ditches were established with the loose earth packed on the inward side to create earthen mounds, sculpted to form great barriers.

Much of what remains today are massive sculptures and artifacts and the adaptive reuse (ceremonial buildings and earthen terraces, etc.) that the Mayan culture built upon these existing Olmec foundations. Around 200 AD, the technique of RE was also used in the Americas; the Teotihuacan Sun Pyramid was constructed around 200AD in the Mexican Highlands, using approximately 2 million tons of RE (metmuseum.org, retrieved 2007).

Eastern Orient

Rammed earth also characterized massive construction projects in India and China primarily used in military defense.

India

RE came to India by way of the Arabian Peninsula. Ironically, the earliest RE buildings that still stand are Buddhist structures, such as the Tabo monastery built around 1300 AD.

These Buddhist structures were constructed of RE, a traditional method gradually replaced by adobe brick. Many of these monasteries were constructed in rammed earth, with the walls generally wider at the base and tapering to the top. This method of wall construction combined with additional horizontal and vertical ties placed in the walls provided greater seismic resistance. Generally the walls are devoid of openings with the only source of light being a roof-light or the doorway. Openings in walls are considered stress points compromising the integrity of the wall during earthquakes and seismic activity.

Buddhist monasteries continue to be the most revered buildings in this region, so generally the highest quality building technology is used for these edifices. This tradition lasted until around the 12th century. Because of marauding armies of Chinese and Mongols passing by way of Tibet, these monasteries changed from a religious sanctuary to a defensive center. This shift to a defensive nature required the monasteries to move to hill top sites. The move away from the valley possibly started the construction practice of using RE. The hill tops were lacking a sufficient supply of timber; earth and stones were substituted as building materials (Chaudry, 2003).

An example of this monastery fortress type structure built in 1450 is the Basgo monastery located in the Ladakh region (Jaquin, 2007). The fortress is now in ruin, while the monastery is still inhabited. The writing contained in the Silpa Sastra, a religious text, contains documentation on the stabilization of soils including compaction, rearrangement, addition and removal of soil particles, chemical reactions (hydraulic lime) and natural heating techniques (Basu, 1997).

This region of Ladakh also is credited with having a nine story building under current restoration (funded by the Aga Khan foundation). It was constructed of RE in 1666, possibly for use as fortification by the Shia Muslims that settled in the region from Balitistan in 1555-1610 (www.dur.ac.uk; Paul Jaquin's website, retrieved 2007).

China

In about 5000 BC, RE construction was being used in China (Bourdon, 1995). The Great Wall of China begun in 8 BC was built, rebuilt, and maintained for many centuries to protect the northern borders of the Chinese Empire from feuding neighbors. The Great Wall is a mega-structure considered the world's longest continuously man-made structure, stretching about 4,000 miles. Because of continual feuding, this wall was built to withstand the attack of small arms such as swords and spears, and the earliest sections of the wall were mostly made by stamping earth and gravel between board frames.

The Hakkas in Fujian Province in southern China have a long recorded history. They lived in a special style, magnificently shaped residence unequalled among folk residential housing of this time period (Lau, Garcia, Ou, Kwok, Zhang, Shen, Namba, 2005).

There were two large-scale migrations of the Han people coming from the Central Plains to the southern part of China in 265-420 and in 618-907 respectively. The wars in the north forced distinguished families to move southwards. These people eventually settled down in modern-day Guangdong and Guangxi, which was quite backward at that time. They lived in close-knit, compact communities that formed what is known as

Hakkas (Lau, et al., 2005). The building method they choose was RE as a traditional building material to create their residential houses. There are two kinds of RE buildings: square or rectangular and circular ones. Both have a large space in the center and come in various sizes. The average structure has three or more stories (some as tall as 5 stories), with all but the first floor generally lined with windows. The RE walls on the outer circle are often more than two feet thick with no openings to the outside with the exception of small perforations (Lau, et. al., 2005). Obviously, having survived years of warfare, these were designed with a strong defensive characteristic (Lau, et. al., 2005). RE buildings boast very good ventilation are considered to be earthquake resistant, fireproof and a very solid building material. The Hakkas' residences have survived without collapse in this region of frequent active earthquakes. The success of resistance by these structures can be attributed to the geometry of their design and the ingenuity of construction techniques (Lau, et. al., 2005).

The Chinese, like their Middle-Eastern counterparts, enjoy the properties of thick walls, because their climate is very cool in the summer and warm in the winter (Lau, et. al., 2005).

Roman Empire (Modern Europe)

In about 1000 BC, the Phoenicians began building with "stuffed earth" (RE), and introduced it to the Rhone valley around 2000 years ago. Much of the Roman city of Lyon was constructed with RE. The Phoenicians found that the glacial soils washed down from the Alps provided a perfect soil for RE construction method (Jaquin, 2007). The Rhone Valley is still populated with these structures and used by modern inhabitants

(Tibbets, 1989). This region of France is considered to be the inspiration for Francois Cointeraux to establish of the *School of Agritecture* in 1791 (Lee, 2007). Francois was very passionate about RE construction. He conducted numerous experiments and saw it as a way to vastly improve the quality of life of the common individual (Cody, 1990). These RE structures are estimated to be centuries old, most with only cosmetic rehabilitation and refinements. Often, in modern construction old RE structures are used as the foundation for new buildings or additions.

The Romans uniquely retained the traditions of many of the cultures of their conquest and introduced RE construction to Europe, especially in the regions we know as France, Germany, Spain and Italy. In the writings of Pliny the Elder (Natural History, XXXV, 48 AD Written around the year 50 AD), he mentions the invasion of Hannibal of the Roman Empire in North Africa and Spain. Pliny records that there were many walls framed of earth in Africa and Spain. Pliny described the process of “stuffing earth” (RE) into a closely packed frame created by two boards one on each side. This type of wall had lasted for ages, was undamaged by rain, wind and fire, and the walls were stronger than quarried stone (Pliny’s Natural History, XXXV, 48 AD Written around 50 AD as cited in Jaquin, 2007).

The Roman Empire expansion brought the process of earthen construction with its conquests and the convolution of the local building techniques. This methodology can even be tracked to settlements in England, Scandinavia and Russia. The Romans did not make use of rammed earth for very long, because they soon developed a form of concrete that was far more suited for their building construction needs.

Conforming to archaeological evidence gathered around the ancient city of Carthage on the hill of Byrsa, one can ascertain that RE was used in the construction of common housing (hustonrammedearth.com, 2007).

In about 100 BC, Marcus Vitruvius Pollio, a Roman architect and engineer wrote *Des Livros de Architectura*, a systematic compilation of the construction techniques of the Romans and Greeks (Jaquin, 2007). This masterful work includes RE construction techniques, specifically mentioned is the process of RE construction being used at Massalia, the modern city of Marseilles, France. Translated volumes of Vitruvius' writings are still being used by architecture schools as reference guides in planning, design and construction education.

Early Europe

The origins of RE in Spain and Portugal are traceable to the end of the ninth century. RE was cheaper to build than the common practice of using ashlar blocks (Jaquin, 2007). Ashlar is a squared building stone cut on all faces and placed adjacent to other stones and has very thin mortar joints.

Literary sources insist that RE was used during the Taifa period (912-1031) where earthen construction was quicker to construct with and more durable, especially in military construction (Graciani & Tabales, 2003).

Centuries later during the late 1700's, German immigrants that were driven to Russia to escape hardship and persecution from their motherland mingled their building traditions with their new found neighbors, the Russians. During this same time period, Scottish builders working in Russia added to the knowledge and tradition of rammed earth design and construction by borrowing from the Scots. Earth construction was used predominately during much of Scottish history (Makhrov, 1997). The Russian architect Nicoli L´vov designed several large scale projects involving the pise´ method. L´vov often relied on the assistance of Scottish builders Menelaws, Cochane, and Cunningham (Makhrov, 1997). One such project was Priority Palace in Gatchina, the only L´vov earth structure to have survived.

European Migration to the New World

Rammed earth architecture in Russia was a product of the amalgamation of the Scottish influence in the North and the German methods in the South. The culminations of these methods were introduced in the United States in the eighteenth & nineteenth centuries.

Scandinavian, German and Russian Influence

The Scandinavians applied traditional trades learned from their Roman experience to the lands of their conquest (Dobson, 1936). Greenland, a Danish protectorate until the twentieth century, has scattered remnants of rammed earth and sod structures.

Techniques of earth blocks were brought to the United States with the immigrants from Scandinavia and England. Their houses were built with patches of earth made from the top layer of a loamy soil with grass on it layered into blocks. These blocks were turned upside down and used like bricks to form walls without mortar (Minke, 2000). These earthen structures were referred to as "soddies."

In the 1880's, the United States invited many Scandinavians and approximately 120,000 German-Russians to settle in various parts of the Great Plains. They brought their building practices with them (Carlson, 1981). These traditional practices were pushed further into the Northern Central Plains along with the integration of the traditions of the Plains Native Americans, (the tribes of the Illinois, Mississippi, Omaha, and Pawnee in particular). Along with the Native American tribes, these settlers used the process of ramming earth mixed with the process of laying strips of sod to create habitable housing. The original housing designs were abandoned for larger and more durable RE (*fachwerk*) houses. The German pioneers were experienced with *fachwerk* and stone masonry. This mode of housing used the cheapest form of building materials, although it was labor intensive and could be erected quickly (Carlson, 1981). The earthen house was soon abandoned for other house building types based on folk architecture and became an indication of perceived economic success (Carlson, 1981).

Many courageous European settlers migrated to the Southern Central Plains and practiced their home building skills honed in Europe, mingled with traditional methods of rammed earth and adobe of the Mexican, Spanish, Hopi, and Anasazi cultures.

The Spanish influence brought to the New World mixed with Mayan techniques, Olmec influences plus the re-advent of cement. In 1549, the conquest by Spain of the New World brought the Spanish (derived from Arabic) styles of building with RE and adobe to South and Central America.

Construction of a church was begun in 1720 by Jesuit missionaries employing indigenous people as laborers. These missionaries were expelled from Brazil in 1759;

therefore the church was left unfinished. This church is one of the few remaining examples of RE construction in Brazil. This architecture followed traditional Jesuit building techniques used in Spain and Portugal, a Romanesque style (Pecoraro, 1993). The RE technology for this building was imported from southern Portugal integrating the native RE traditions, creating a European architectural style. This building is still standing and is under the care of conservationists (Pecoraro, 1993).

From Peru, the adobe method migrated northward through Mexico and mixed with the indigenous housing methods that were used in California. Across the American continent in Florida, the Spaniards were constructing their first colony using RE, "tapial" in Spanish (Vinuales, 1993). Tapial was developed using soil and ground seashells as a binder, rammed into heavy formwork. The Spanish settlement, now referred to as Saint Augustine, Florida was constructed of tapial earthen methods (Vinuales, 1993).

Modern America- United States

In 1850, the Church of the Holy Cross was built of RE in Sumter, South Carolina. This church has withstood earthquakes, hurricanes, and more recently repairs that have been performed with concrete. This is an example of one of the few RE structures built in the Southern United States.

John Wright was the editor of *Prairie Farmer* 1843-1855 and published 40 references to rammed earth in this periodical. Unfortunately for the rammed earth methodology, the spread of the railroad west began the decline of earthen construction with the introduction of cheaper and better building materials to the prairies (Jaquin, 2007).

Around the end of the nineteenth century, the United States government was very interested in protecting its new territories and newly acquired citizens. The military was dispatched to the central plains to have its presence felt. Since ancient fortressing was successful with walls constructed of earth; the early military forts of the central plains and intermountain west were based on similar designs. However, this model patterned after ancient fortressing did not occur in the beginning, as one might imagine. The military outposts in the Northern Central Plains were often faced with a construction dilemma, where to get materials to build a fortification. For example, in 1849, when the U.S. Army acquired the trading post at Fort Laramie, the troops were able to obtain timber a short distance away, but within two years they had to travel twice as far to find suitable wood; within fifteen years, the distance traveled had quadrupled (Hoagland 1998).

In 1873, the quartermaster general's office published a pamphlet detailing the methods of construction with pise´ and concrete as a binder to be used in fortification construction on the frontier (Hoagland, 1998). A majority of the pamphlet's information on pise´ was reprinted from the Encyclopedia of Civil Engineering that had been published previously by the Institute of Civil Engineers (Hoagland, 1998). The knowledge of the subject of RE was known, but was not an established and viable method until it became absolutely necessary.

From 1780 until about 1850, RE construction enjoyed a period of popularity in the United States until mass-produced fired bricks and sawed lumber became readily available. This new material technology of bricks and lumber could be used to build houses easily and more quickly and was considered more modern and elegant than constructing with dirt (L. Hall, 2006).

Nineteenth Century Methods Modernized versus New Twentieth Century Technology

During World War I and the Great Depression, the construction material industry experienced supply shortages which brought rammed earth techniques back into favor for the next two decades (Hall, 2006). Frank Lloyd Wright designed houses to be made of rammed earth.

In the aftermath of World War II, the housing market was booming once again. The housing industry turned to manufactured building materials to quicken the pace of construction (Hall, 2006). The methodology of RE was once again brushed aside only to be re-popularized in the environmentally conscious 1970's (Hall, 2006).

RE construction techniques for thousands of years were taught personally by one generation of builders to the next. In early twentieth-century America, such a network of experienced builders did not exist. The U.S. Department of Agriculture published a manual entitled *Rammed Earth Walls for Buildings* showing average people how to build their own homes. Between 1926 and 1950, the U.S. government sponsored research projects designed to improve the methods and quality of RE construction which were published in academic journals and hundreds of articles were written on the subject appearing in major trade journals and popular magazines (Hall, 2006).

In 1926, T.A.H. Miller was sent to investigate the Church of the Holy Cross mentioned earlier. His research culminated in the now famous published report entitled, *The Farmers Bulletin No. 1500*, which discussed in detail the virtues of the RE construction process to be extolled among the general population. Concurrently, at South Dakota State University, R.L. Patty, L.M. Minium, and H.H. Delong had been performing tests on RE since the 1920's and 1930's (Delong, 1959). In 1937, this type of housing was supported by governmental research in Garden City, Alabama. As part of President Roosevelt's New Deal program, Thomas Hibben, developed ideas for new methods of RE home construction. Around 1937, the suggestion was put forward and Hibben built seven experimental rammed earth homes in Garden City, Alabama (Merrill, 1947 as cited in Cassell, 1993).

After being influenced by the *Farmer's Bulletin No. 1500,* an article in *American Home magazine,* and with Hibben's work, David & Lydia Miller and associate J. Palmer Boggs (a professor at Oklahoma State University in the 1940's) decided to design and construct a home built of RE (Miller, 1982). With the completion of the first house, the project was so successful that multiple homes were designed by Boggs and built by the Millers in the Greeley, Colorado area. Boggs made use of his previous experience to produce newer designs that could still be called advanced by today's standards.

However, in the 1940's, the design was a radical departure from normal building practices (Miller, 1982). The Millers continued to live in their second RE home built in 1945 (Miller, 1982). David J. Miller has been compared to the stature of Babe Ruth, stating that David is to rammed earth, what Babe Ruth means to baseball (Cassell, 1993). The Miller's were instrumental in writing published reports extolling the virtues of RE (See Michener Library archive collection). These writings have since been donated to the

University of Northern Colorado archives. The Millers also established the Rammed Earth Institute International in the 1980's (now defunct).

In 1941, using Professor R. L. Patty's research as a pattern, Eric Hubbell constructed a number of homes on a Native American reserve in North Dakota (Patty, 1942). Following the completion of these projects, the US Bureau of Standards put together a report entitled, *BMS 78* detailing the compression tests performed on RE blocks (Jaquin, 2007).

Twenty- First Century and Beyond

Pise´ de terre or simply pise´ is an age-old building method that has seen numerous revivals in popularity especially in recent years. People are seeking a low impact, zero carbon building method using natural materials (www.ebaa.asn.au; the website of The Earth Building Association of Australia, Inc). Since the OPEC Oil Embargo and the energy crisis in the 1970's, there has been a rejuvenation of alternative housing design.   David Easton has been affected by many of the publications previously mentioned and has brought a resurgence in rammed earth building. In Fiddletown, California, David began with a project restoring a small RE building designed in 1850 by Chinese immigrants. Easton has established Rammed Earth Works, CA to further promote the use of RE (David's website; rammedearthworks.com).

Continued research has been promulgated and published by the U.S. Departments of the Army, Agriculture (USDA), the Bureau of Standards, Housing and Urban Development (HUD), and Agency for International Development, as well as the United Nations (UN), to list a few. A USDA report stated that RE homes could last indefinitely if constructed properly and could be built for the same costs of a standard frame. When designed correctly, the earthen abodes were shown to be considerably less expensive to heat and cool (Fathy, 1986).

Today, the largest innovations in earthen construction techniques are made in Australia, France and Austria (modern RE projects are discussed further in Chapter 5). In New Zealand, the process of RE is the third most popular earth-building technique behind adobe brick and pressed soil-cement brick construction (solidearth.co.nz, retrieved in 2007). Modern walls of earth are often left bare to reveal an appealing strata pattern from the ramming process. The wall surface can be sculpted to create more texture if worked on while the earth is still damp (solidearth.co.nz, retrieved in 2007).

To conclude this section of historical background, Fathy indicated the impetus of architecture from the historical to the present as the advancement of technology for the mastery of man over the environment. If the challenge is small, man doesn't spend much effort to be creative with the solution. Most designers do not comprehend the context of the environment and fail to understand its meaning (Fathy, 1986).

Rammed Earth and the Construction Phase

Rammed earth requires some knowledge of traditional methods taught mostly by experience passed from generation to generation. Consistent workmanship is critical for both the appearance and the strength of rammed earth walls; therefore the soil excavated during site work has to be of high quality.

While RE may be aesthetically pleasing, the strength of the wall is of the utmost importance. Unlike bricks or cement, RE does not consume vast amounts of energy (embodied energy) to bake it in an oven, and noxious gases are not released during its manufacture (Benge, 1999).

Typically, a small amount of additional materials are required to stabilize the earth. Depending on the type of soil, cement, lime, or even dung can be used, and sand may need to be added to clay soils (Benge, 1999). Earth is not a resilient material so there are structural problems involved in resisting any lateral forces imposed on the RE structure, particularly those associated with earthquakes. These issues have been resolved by placing steel reinforcement rods vertically and horizontally in the walls and adding a timber or concrete bond beam around the top of the walls to tie them together. Some experimental work is being performed to find a way of using locally-produced fibers, such as flax, to strengthen the structures without the necessity for steel reinforcement (Benge, 1999).

Moisture is another challenge for earth building. High rainfall and strong winds mean that care must be taken in designing earth buildings to prevent dampness in the walls. Whatever the type of earth building, adobe bricks, poured earth, or pise´ (RE), the following concerns need to be adequately addressed prior to the application for a building permit: (Glick 2008)

- Soil testing to ensure sufficient stabilization,
- Foundation and floor systems that prevent dampness from wicking upward,
- Sufficient foundation height to ensure proper site drainage to prevent flooding in a 50- year storm,
- Expansion joints in the finished plaster to control cracking,

• A finished coating on the exterior that resists moisture penetration. A permeable finish system to ensure proper moisture movement out of the RE wall if moisture becomes present, a design for RE construction to ensure zero moisture penetration into the wall system is critical,

• Adequate flashings at all openings,

• Outward sloping window sills,

• Proper allowance for vertical shrinkage in all window and door openings,

•A roof that does not leak, and

•Sufficient roof overhangs to shelter the walls below and allow maximum solar gain in the winter.

Advantages of Earth-Sheltered Housing

A graphic comparison of several home construction materials by construction type is shown in Table 2.1.

Table 2.1 Construction Methods & Material Comparisons From Earth and Sun (RE) Construction Company website, retrieved 2007

Category	2x6 Wood Frame	Adobe	Straw Bale	RE
Wall Thickness	6 In.	6 In.	22-28 In.	18-36 In.
Maintenance	High	Low	Moderate	Low
Fire Resistance	Fair	High	Fair	Very High
Pest Resistance	Very Low	Moderate	Low	Very High
Energy Efficiency	Fair	High	Moderate	Very High
Thermal Mass	Very Low	Moderate	Low	Very High
Building Style	Very Versatile	Southwest	Versatile-Thick Look	Thick Look
New Mexico State Building Type	Standard	Standard	Alternative	Standard
Cost	100%	108%	72%	110%
Durability	75-125 Yrs.	75-200 Yrs.	Unknown	200-600 Yrs.
Acoustic Ability	Very Low	High	Moderate	Very High
Ability To Stop High Velocity Projectile	Very Low	High	Moderate	Very High
Temperature; Variance Floor To Ceiling, Fahrenheit	8-12 °	2-3°	8-12°	2-3°

There are other ecological and safety advantages of earth sheltered housing:

- Long-range economic benefits,
- Considerable reduction in fuel costs,
- Reduced maintenance expense,
- Reduced insurance rates, and
- Land use efficiencies (Impson, 1992).

It is estimated the fuel cost reductions are from 50 to 70% of standard construction (British Standard 7543:1992 as cited in Impson, 1992). Energy consumption is minimized by reducing or eliminating air infiltration through the wall mass plus “the heat storage capacity of concrete” (RE has similar heat storage characteristics to concrete mass) (Porteous, 1992 as cited in Benge, 1999). “The earth has erroneously been described as an insulator. Actually, the earth's mass acts to retain and disperse heat energy and reduce temperature changes,” a feature that produces consistent and even temperatures (Thomson, 1999, as cited in Benge, 1999). In underground houses, an interior ambient air temperature of 80 degrees or less is common, “while outside temperatures reach or exceed 100 degrees” an attribute comparable to above ground RE structures (Shaw, 1991, as cited in Benge, 1999).

One difficulty with rammed earth is that strict limits have to be placed on shrinkage to eliminate cracking; a sandy crumbly soil with clay content around 15% is best (earth building association of New Zealand website, 2007). Often cement plus hydrated lime is added to improve durability and for shrinkage control. This, however, isn't always necessary, as many successful structures have been built from suitable soil without such additives. Some insurance companies reduce RE insurance rates because of the non-flammable and earthquake resistant attributes of earthen construction.

Building Codes

"Building codes are perceived by many as a challenge to building innovation, including sustainable approaches to building and development, *green building*. These barriers are both technical and non-technical in nature," (Eisenberg, Done & Ishida, 2002).

The traditional techniques of RE construction are not costly. The materials (earth) are generally free for the taking and the construction labor needed is typically available. People in the world who are considered impoverished or with minimal means can figure out how to build their own home with rammed earth, it is within their understanding (Shearer as cited in Fathy, 1986).

Common obstacles to earthen construction in developed countries are modern building codes, urban regulations, and a general unfamiliarity with this building methodology. Although RE has a ten thousand year track record and is considered a traditional method of construction, the increase in regulations and liability is making it more difficult to revive this once prevalent building methodology.

Energy codes provide a basic way to build energy efficiency measures into our building industry. A building designed and constructed for efficiency will provide lower energy bills and more comfort for consumers (Benge, 1999). It has been recommended by Eisenberg, that construction industry support improved building energy codes through several efforts: (Eisenberg, 2000).

- Upgrading model codes at the national level,
- Supporting adoption of model codes, and
- Helping governments with jurisdictional authority implement model codes.

Building codes are written by organizations like the International Code Council (ICC) which produces the International Building Code (IBC), a model code. In the United States, the two common code classifications are prescriptive and performance based. Presently, there are two basic types of building codes in use, prescriptive or performance-based. The first, *prescriptive* appears, to be the most prevalent building code. It is a process that indicates what individuals need to do in order to satisfy the code requirements. Prescriptive codes can be very rigid, specific and restrictive. In the past 100 years, building regulations have been prescriptive, describing what must be done and how it is to be accomplished by a generally accepted "checklist" (www.greenhomebuilding.com, 2006). By nature, such systems of governance are very restrictive and cannot cover every foreseeable circumstance and situation encountered on the construction project. "Code officials are charged with the responsibility for protecting the public welfare. To do so they depend on their ability to interpret the technical requirements of the codes and whether technical merits of the alternatives meet those requirements" (Eisenberg, Done & Ishida, 2002). The code officials rely on tests and certification from independent testing institutions.

Recently, the performance-based codes are increasingly being used. Performance-based building codes simply state what outcome must be achieved; they are very broad and versatile. Performance-based building regulations should encourage the use of local materials, traditional construction methods, and new technology that will result in cheaper construction (www.greenhomebuilding.com, 2006).

Prescription-based Building Codes

Under this system, trying to comply with national and local building codes can be arduous for individuals wanting to build with natural materials. It becomes more tenuous when building with anything that is experimental in the design concept or building technology (www.greenhomebuilding.com, 2006). If the application is not in the code, the acceptability of the presented method or materials needs to be proven prior to adoption by the local building official.

Most codes are subject to interpretation. Therefore, the Uniform Building Code does allow discretion of the inspector to follow different interpretations of the code, if the inspector feels that the intent of the code is met. This is an exception to common procedure, because there is a disincentive (www.greenhomebuilding.com, 2006).

This description of current building codes has inadvertently squelched innovation in building technologies and subsequently innovation which is vital to sustainable architecture (www.greenhomebuilding.com, 2006).

The specifications of any code are developed and derived from historical building practices, data and accepted standards. With the usage of such natural materials as straw bale, cordwood, adobe, etc. if allowed at all, must adhere to the accepted scope of the code. Usually in these natural methods of construction, materials may be used as 'infill', but are not allowed to be used structurally to support any weight of the building (www.greenhomebuilding.com, 2006). The purpose for having building codes and regulations are the response to historical safety and health issues.

There are occasions the accepted codes have ignored health and safety issues specifically; indoor air quality, the toxicity of materials and chemicals used in building construction, or the impacts on manmade & non- renewable resources and often the impacts on global climate change (Eisenberg, et al, 2002).

Performance-based building codes

Performance codes are the other option available to code officials. This approach to codification is equivalent to a guidebook. The focus is on the desired qualities of the intended canon, and they increase the use of innovation and alternative methods and materials (Benge 1999; Eisenberg, et al, 2002). The difficulty associated currently with this concept is the proof. There appears to be a shortage of historical data to quantify a baseline for measurability. The resurgence of performance-based codes has a short history (Benge 1999; Eisenberg, et al, 2002).

According to Benge, performance-based building codes can facilitate and accommodate a diversity of alternative construction methods, which satisfy the regulators, conservationists and lawyers alike while providing improved, more economical, and efficient buildings (1999). The writings of Benge have detailed the usage of performance codes in New Zealand (1999). These studies are coming from a relatively small country; however, they are in the forefront of this protocol. Alternative construction methods may include earthen buildings, straw bale, and log construction for building houses. The use of performance-based building codes to assess materials or systems that are not current standard construction can be used in any country taking local considerations into account. Benge suggests that code compliance needs to demonstrate a “satisfactory measurement” for code officials to accept it. Benge has suggested that the performance criteria of New Zealand Building Code clauses encompass structure, durability, external moisture, to measure the adequacy of the proposed systems: (1999).

Structure

The structural strength of a building can be “demonstrated by recognizable methods of calculations” (Benge, 1999). Obtaining engineered drawings and specifications that will attest to the structural stability might be all that is necessary.

Moisture

Moisture, from external as well as internal sources are a challenge in the construction of buildings and especially critical in RE structures.

External

Keep the water out of RE or other constructed buildings; surface water needs to drain (slope) away from the structure to prevent penetration into the building envelope. The addition of extended roof overhangs and a “plaster” type coating on the exterior walls are preventative measures taken to ensure moisture does not enter building envelope. A non-cohesive material (gravel) under the floor structure is essential to prevent wicking in structures, where there is a slab on grade and ground water is a concern, especially in RE construction methodologies.

Some public perceptions of rammed earth as being a material with low climatic durability are somewhat misguided but not entirely unfounded. Rammed earth construction is most popular and performs well in warmer and dry climates. Further, research is essential in determining the relative application of rammed earth in more temperate and damp climates (Hall & Youcef, 2004). Since RE walls are monolithic in nature, the possibility of capillary movement of moisture within them could present a problem (Hall & Youcef, 2004). "In a suitable soil, the ratio between the total specific surface area (SSA) of the aggregate fraction and the mass of the binder fraction appears to be positively linked with the rate of capillary suction in rammed earth" (p. 269). Hall & Youcef (2004) concede that there is significantly less water absorbed due to capillary suction and at a slower rate, than conventional modern masonry materials. These findings postulate this conclusion in terms of rate and quantity of moisture ingress due to capillary suction. A later study by Hall (2007) comes to the conclusion that "after five days of exposure to static pressure-driven moisture ingress there was no evidence of moisture penetration or erosion" (Hall, 2007 p. 145). This study was conducted in the United Kingdom with sample RE walls. High pressure nozzles were aimed to a specific point on the wall to attempt to create erosion. "The embedded sensor array detected no significant increase in the relative humidity or liquid moisture content inside the test walls from a minimum depth of 150 mm (5.9 inches) away from the exposed face" (Hall, 2007, p 145). The test samples indicated all have a negligible risk of "internal or interstitial condensation" (Hall, 2007, p. 145).

Internal

Internal moisture may be enhanced in a tightly constructed building envelop and needs serious consideration in the design process to ensure the health and safety of occupants.

In conjunction with moisture, the occupants create moisture through household tasks resulting in condensation and thus growth of fungi and mold within houses as long as there is a food source, water source, and a favorable temperature.

Durability

The durability provisions of the building code are there to provide a minimum level of expectation to the consumer as to how long that building will last also referred to as the useful life of the building. Buildings are designed to withstand environmental factors based on local climates with the expected outcome from any event, being the building will perform as designed.

Strategies for Code Acceptance

To create additions to codes, most individuals will need a champion to research, test and propose change like the Development Center for Appropriate Technology (DCAT) in Tucson, AZ. Eisenberg and others established DCAT to perform the testing which is prohibitive for the average builder and homeowner to afford. As a result of the work of DCAT, changes in building codes do exist, for example the state codes of Arizona and New Mexico now include adobe and RE, as well as graywater usage standards.

Eisenberg, et al. (2002) suggests the following ideas to achieve code approval:

- Provide supporting technical data (as much as possible; testing can be arduous, painstaking, and financially prohibitive for most private companies), and
- Provide examples of relevant successful case studies (recent or chronicled data), and start the process early in the design phase. It becomes imperative to educate the local building officials early in the building process to prevent money spent on something that is not buildable to code.

Involving the building department staff early facilitates knowledge transfer before the project gets to the code compliance phase. The studies at DCAT indentify education as the first strategy for improvement to the building code (Eisenberg, et.al, 2002). This education needs to extend to builders, building code officials, building designers and the public. These educational sessions can include workshops, demonstrations, pilot projects, and continual testing of potential products, as well as modalities. The suggestion of the research is to increase the participation in the code review and adoption process. The introduction of new building systems and material usage into the dominant building paradigm is no easy task.

Wall Mass and Thermodynamics

The mass or thickness of the walls used to create a structure not only provides protection from the elements and therefore allows a level of comfort for the inhabitants, it also holds up the floor above and roof system. The structural properties, mass, thermodynamics, energy consumption, and efficiencies need consideration in the evaluation of different wall systems.

The wall of a house has a thermodynamic capacity to conduct or resist the flow of heat as it seeks cool. Once the heat overcomes the thermal interface it could be stored in the mass of an RE wall system, as the air temperature cools the warmer air is transferred to the cooler space. The physical properties of a wall also have a level of resistance to the flow/ movement of heat (gain or loss) and air changes. Each building material, man-made or natural, has a certain mass or density. Each retains heat/cold or lets it pass through. Table 2.2, demonstrates properties of certain building materials. Wood is not included because of the minimal thermal mass of wood framed housing, even though the light weight envelope of wood is a dominate feature in the current constructed building landscape.

Table 2.2 Densities, Specific Heat and Thermal in a Range of Materials (Ecospecifier, section 2.2)

Material	Density (Kg/m³)	Specific heat (kJ/kgK)	Volumetric heat capacity Thermal mass (kJ/m³K)
Water	1000	4.186	4186
Concrete	2240	0.920	2060
AAC[1]	500	1.100	550
Brick	1700	0.920	1360
Stone (Sandstone)	2000	0.0900	1800
Fiber Cement Sheet (compressed)	1700	0.900	1530
Earth Wall (Adobe)	1550	0.837	1300
Rammed Earth	2000	0.837	1673
Compressed Earth Blocks	2080	0.837	1740

[1]**AAC;** Autoclaved Aerated Concrete is a precast structural product made with all-natural raw materials

In RE walls some of the heat flow through a wall is stored in the volume of soil within the RE walls. This stored heat will change the temperature of the wall itself (Barbarick, 2004). This temperature change is at a slower rate due to the mass. By the time the heat travels towards the cool inside of the house, it is dark and the heat is welcome for night-time comfort. In the morning, the outside temperature is cooler than the inside, depending on the time of year, and the heat starts to move to the outside of the house. According to Fathy, the study of the thermodynamics of a wall needs to be concerned with air and heat transference. Hassan's research is concerned with cooling because of the hot, arid climate of Egypt; however, his work is equally useful for the temperate climate of the northern Colorado Front Range. All walls constructed for housing will allow some movement of air and heat at the same time creating some resistance to these flows based on the individual component R values of the wall system's U value.

Thermal resistance is referred to as an (R) value, while the reciprocal of R is the conductivity (C) of the wall material.

$$C = \frac{1}{R}$$

The rate of heat and air flow is a useful concept in understanding the comparisons of wall materials and their thermal conductance. The thermal transmittance is the surface resistance plus the rate of heat transferring per unit of measurement through the wall, denoted as a (U; the thermal transmittance) value, also referred to as the reciprocal of the sum of the system R values.

$$U = \frac{1}{R_1 + R_{2+\dots} R_n}$$

The emissivity (ε) or thermal absorptivity (α) of a wall is dependent on its material make-up, density, mass (thickness), ambient air temperatures (on both sides of the wall), and solar radiation. Once the thermal capacity (c_p) of a wall and the time or rate of energy movement is known, then a comparison of wall types can be considered on a level plane for efficiencies.

The U factor is the capacity of a material to transfer heat or cold. The U value and the mass are useful information to consider for more equitable comparisons. Based on the R value alone, there is no comparison of the R values of SB walls (R3 to R19 per inch, depending on the construction) to that of RE walls which have poor thermal resistance (R0.4 per inch), (Chalfoun & Michal, 2003). The wood by itself without insulation and moisture barrier will have a higher resistance to heat transfer. Wood has a lower R value than fiberglass insulation, for example, based on the relative thickness of the two materials. For example; a 2x4 of wood has an R value of 1.25 per inch totaling a 4.375 component R value (Commonwealth Scientific and Industrial Research Organization (CSIRO), 2000). The 3.5" insulation in a 2x4 built wall has an R value of 13-15 depending on the product. RE wall systems are a "breathable" building material even in a compacted state, and therefore it has very little resistance to heat conduction (CSIRO, 2000). However, the massing of the earthen material has a slower transmittance than that of wood, brick or block construction. Studies conducted by Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia have suggested that highly massed walls combined with a high R value, by adding insulation, "can perform especially well". Adding foam board insulation to the exterior of an RE wall system before application of a siding material such as stucco, clapboard siding or brick veneer is one solution. The interior can be framed with a stud wall system, fiberglass insulation and a wall board covering can also be applied. The installation of insulation, dependant on the material choice of the builder affects the storage and transfer of heat in the RE wall. CSIRO's findings indicated that high mass by itself is of little value regarding human comfort unless sited in a mild climate (2000).

The temperature related to human comfort within a RE structure changes slowly during a given day, depending on the roof system which can contribute the biggest heat loss in buildings in cold climates. In this regard, there are two issues to consider: solar radiation and mass. First, the solar radiation on the earth's surface and the external ambient temperatures has a gradual variance during the diurnal period, and the temperature inside the building is continuously trying to reach equilibrium in the rate of heat gain and loss. The other consideration is that the mass of the building walls, particularly RE wall systems, do not respond instantly to external changes. This "thermal inertia" happens in a matter of minutes to a period of several hours for an equilibrium change in wall temperature (Fathy, 1986). The ideal interior climate of housing would need to provide a degree of comfort by leveling the parameters encapsulated in the governance of heat gain and loss (Fathy, 1986).

The nearest current standard building practice that closely correlates conceptually to the mass of an RE wall system is a basement foundation wall system. Concrete is poured into walls and backfilled on the exterior with compacted excavated earth. The ambient temperature in a basement, in the Front Range generally hovers around 56 °F at a depth of 6 feet (American Society of Heating, Refrigeration and Air conditioning Engineers ASHRAE, 1999). The guideline established by the ASHRAE applications handbook, suggests 52°-56° with a deviation of +/- 4°, in the area of this study (American

Society of Heating, Refrigeration and Air conditioning Engineers ASHRAE, 1999). A RE wall can have a similar ambient temperature due to the wall mass and the thermal inertia mentioned above. The scientifically established temperature for human comfort, as described by the London School of Hygiene and Tropical Medicine, is in the range of 68-72°F, (As cited in Fathy, 1986). This comfort range is also accepted by ASHRAE standard 55-1992 including a level of humidity between 30-60% RH (relative humidity) (ASHRAE, 1999). Human comfort related to RH, if below 25%, feels uncomfortably dry. A RH level above 60% feels uncomfortably too moist. The optimal human comfort suggests the RH to be in the range 25 - 60% (ASHRAE, 1999). The relative humidity for this study area is low and not significant (Palmer Z index, from the National Climate Data Center, NOAA, September, 2004). Thus the ambient temperature in the NoCOFR basements needs to be increased by approximately 14°F to reach a human comfort level. The mass of the concrete and the earth can contribute to this phenomenon; thermal mass tends to even out the ambient diurnal temperature range within a building, (Bannister, P., Taylor, P., Ardren, C., & Schmidt, M. 2008). Earthen walls are used to "moderate indoor temperature fluctuations" (Sha, K., Deng, X., & Cui, C., 2000).

In earthen structures, the exhausting of heat through leakage can be reduced, the conduction of heat is diminished, and the heat/cooling storage capacity is increased (Sha, et.al. 2000). Wall mass and density of building material has a direct relationship to the thermal comfort of building occupants.

Thermal Comfort

Mass is an essential aspect of energy-efficient design. However, mass alone will not create a thermally comfortable building environment. The thermal comfort of an individual exists “when the body’s heat loss equals its heat gain or vice versa” (ecospecifer.org, Section 2.1). According to the thermal comfort technical guide of the organization Ecospecifier, the body exchanges heat through five methods. The percentages of each are displayed in Fig. 2.1.

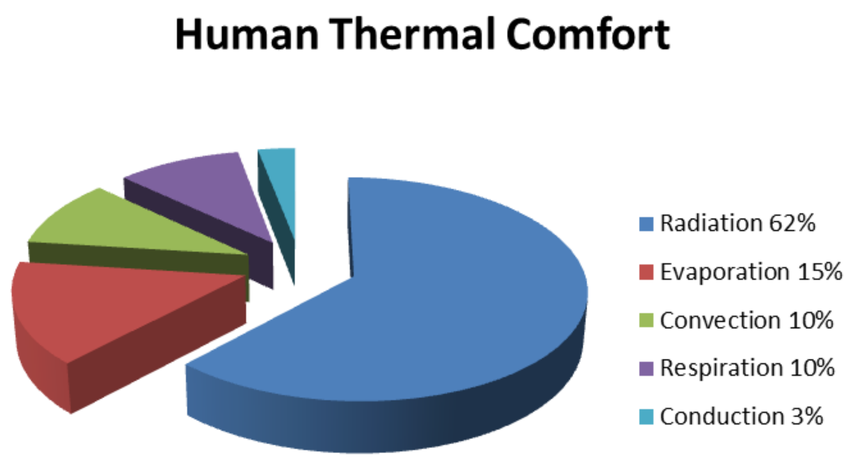

Figure 2.1 Breakdown of Body Exchanges by Percentages (ecospecifer.org, Section 2.1)

To clarify these terms, radiation is the transfer of energy from the human body. Evaporation is moisture leaving the body (sweat) and convection is heat transferred through air movement (hot air is lighter and rises, while cold air is denser and falls). Respiration is the inhalation and exhalation of air: breathing, releasing heat energy from the body to the air directly. Finally, conduction is the transference of energy through touch and contact with objects (walls, floors, etc.).

When considering “normal comfort” conditions inside a building, it is important to examine the radiation properties of the structural surfaces as well as the effect of the air temperature. “Thermal mass influences bodily comfort by providing heat source and heat sink surfaces to support the radiative heat exchange comfort processes” (ecospecifer.org, section 2.3). In situations of high thermal resistance (R value) and low levels of thermal mass (SB construction, etc.), rapid heating and cooling will occur. These rapid temperature swings can be lessened by the use of proper building overhangs, tight building envelop, natural shading in the summer months, proper usage of convection and other “green” principles in sustainable construction. Conversely, low levels of thermal resistance (more U value) and high thermal mass (RE construction, etc.); significantly reduce the necessity for heating and cooling (Givoni, 1981). Buildings incorporating thermal mass have a resultant indoor temperature far more stable than the external temperature (ecospecifer.org, section 4.4).

The inclusion of thermal mass in building design is only a part of an integrated approach to sustainable design. This design approach should include; correct siting for seasonal solar orientation as well as site integration considerations, appropriate use of natural and/or mechanical ventilation and appropriate back-up heating and cooling sources. The consideration of appropriate wall areas (between solid and window spaces) and treatment of windows, insulation is to be included in appropriate design solutions.

In using various kinds of earthen construction techniques (adobe, RE or compressed earth blocks), thermal mass, with their inherent time lags of 10-11+ hours, perform more efficiently (allowing the nature flywheel to occur) if they are either left unsealed or finished with a ‘breathable’ coating on either side of the wall (ecospecifer.org, section 4.5).

In relationship to thermal comfort of the human inhabitants, a direct correlation is with time lag or perm rate and the properties of air flow and its conduction through the thermal mass and density of the walls.

Time Lag

Another element of building materials to be scrutinized is the relative time of heat/cold to permeate the product. This phenomenon is referred to as time lag, or ‘perm rate’, which is the duration in hours for heat/cold to be transmitted through the material. Permeation, in the geological sense, is the rate of penetration by a liquid, gas, or vapor through a solid object, and is related to a material's intrinsic permeability, (stated as pervious, semi-pervious or impervious). Permeability, rated in perms, is a measure of the rate of transfer of, heat or cold through a material. There are established standards for measuring the transmission rate. Air and Vapor ratings are different from liquid calculations. Air/Vapor of a given thickness is rated according to Permeance by dividing the permeability by the thickness of the material of penetration. The diffusion or migration of the permeability known as Fick’s Law is used in the construction industry (Michon, 2003); (*For further study see Fick’s Law & Darcy’s Law*). The thermal dynamics between SB and RE structures discussed previously are closely related to the time lag/perm rate. More specifically, the distance that heat/cold will travel through, without obstruction, e.g. insulative layer, at different time and penetration rates depending on the density and thermal mass of the building material. This time lag and perm rate are important to the proper design to meet the heating and cooling needs of a residence. The diurnal temperatures of the NoCOFR can be significant due to the weather patterns. The range of the diurnal temperatures can be stabilized by the time lag factor. The outside temperature extremes (cold or heat) are in delay or holding (transmitted or resisted), depending on the building materials and can minimize or mitigate the need of heating or cooling the thermal comfort zone inside the house. The internal heat gains of people, lights, and appliances can also be absorbed and stored in the buildings structure (AIA Research Corporation, no date).

Time lag figures of numerous construction materials vary by thickness and are illustrated Table 2.3.

Table 2.3 Time Lag of Building Materials (From Baggs, SA, JC, DB, 1991 and Think Brick Australia, 2006)

Material (Thickness in mm/in.)	**Time lag** (hours)
Insulated Brick Veneer	5.0
Concrete (250/9.84)	6.9
AAC (200/7.87)	7.0
Double Brick (250/9.84)	7.0
Adobe (250/9.84)	9.2
Rammed Earth (250/9.84)	10.3
Compressed Earth Blocks (250/9.84)	10.5
Sandy Loam (1000/39.37)	30 days

A Few Modern RE Projects

An RE revival of sorts has been happening in North America in the past twenty plus years (see chapter one). There is a measurable increase in residential projects as well as commercial enterprises. Projects since the year 2000 include: a cultural center in Canada (Williams, 2007), a library addition in Wyoming (Casperstartribune.net, April 1, 2008), a Public Employees Retirement Association (PERA) building in New Mexico (personal visit), and numerous homes in Colorado (personal visits).

In the summer of 2006, a newly constructed Nk'Mip Desert Cultural Centre was opened in Osoyoos, British Columbia, Canada. This structure is one of the few commercial projects to use RE walls as the main architectural structure. On the Okanagan Indian reservation, this cultural center was designed to be as unobtrusive on the landscape as possible. The architecture firm of Hotson, Bakker, Boniface, Haden + Urbanistes of Vancouver wanted to create something that would be culturally valuable to the tribe, share their connection to the land, and invoke a sense of belonging. On May 4th, 2007, the Nk'Mip Desert Cultural Centre, a building that features the largest rammed earth wall in North America, received an architectural award from the Royal Architectural Institute of Canada's (RAIC) 2007 Awards of Excellence for innovation in architecture (Williams, 2007).

In the spring of 2008, the first-ever rammed earth public building in the nation was completed to complement the Pinedale, Wyoming Library expansion (Casperstartribune.net, April 1, 2008).

In the spring of 2009, the Public Employees Retirement Association (PERA) building in Santa Fe, New Mexico was completed. According to one of the job superintendents visited with by this author on site, this is the first RE building built with public funds in New Mexico. The Land of Enchantment has a vast history of earthen buildings constructed for hundreds of years; now a public building is RE. The process may be modern and aesthetically stylish; it is still building upon an ancient traditional construction.

Now that the preliminary background has been discussed in this chapter, next the research methodology chosen for of this thesis, an embedded case study will be explored in detail in the following chapter.

CHAPTER THREE: RESEARCH METHODOLOGY

The research methodology chosen for this thesis was a case study; more specifically is an embedded case study of mixed methods. Embedded case studies provide the means for the researcher to integrate qualitative and quantitative methods into a single research study (Scholz & Tieje, 2002; Yin, 2003). The objective is to describe features, context, and a process of a phenomenon (Scholz & Tieje, 2002; Yin, 2003). The phenomenon in this case, is the properties (mass, thermodynamics, etc.) of RE walls in residential housing construction. A paradigm espoused by Yin suggested that this case study was ideal as an embedded case study, where an observer may have access to a phenomenon (RE) which was previously inaccessible. This type of embedded case study is an appropriate approach to a real and complex issue of construction methods (Scholz & Tieje, 2002). This study of the NoCOFR comparison of SB and RE construction is embedded with more than one unit of analysis; individual energy consumption data, cross-referenced with regional (Colorado & western U.S.) and national consensus information (U.S. Department of Energy), to draw conclusions on these facts.

The embedded case study research method relies on multiple sources as evidence in the data collection (Scholz & Tieje, 2002; Yin, 2003). These sources, for this paper are; documentation (utility company data), archival records (e.g. Miller's first hand writings, descriptions & drawings); direct observations (by this author); and physical artifacts, which presented insights into the technical operations of SB and RE construction (Tellis, 1997). This case study approach is a relevant investigation in an environment where the boundaries between the phenomenon (RE) and the context, which are not always clearly evident (Scholz & Tieje, 2002; Yin, 2003). A case study of this nature is a logical methodology to addresses the process (modern RE housing) which is not yet thoroughly researched (Leonard-Barton, 1990). This particular study was an investigation of an individual subject; energy consumption of residential structures built of two differing building methods (RE and SB).

This exploration was for gaining an in depth understanding into which building method, if either, consumed the least amount of energy to heat or cool the residence in a specific geographical location. The study boundary was limited to the occupation or use phase of these individual residences. This case study used a triangulated research strategy (Snow & Anderson as cited in Feagin, Orum & Sjoberg, 1991). This is to say multiple sources of data; utility bills, archival research of past RE structures in the NoCOFR, and comparison to similar studies (Krnjetin & Folic′, 2002; Gossen, 1993 & Taylor, Fuller & Luther, 2007), were used to support the validity of the process and to establish meaning to the research (Yin, 1984).

This study is delimited by the use of a convenience sample based on the researchers desire to look at RE homes built in Northern Colorado. This desire stemmed from the understanding there were RE homes built in this region through a now defunct RE institute in Greeley, CO. While this delimitation is significant it will help to confirm other studies results or show inconclusive results based on a limited number of participants (N=6). In either case the exploratory nature of this study cannot be generalized to any population. In addition to a small sample size, two of the homes in the study may not be occupied on a year-round basis. This may further impact the results of the study.

The data analysis is a combination of scrutinizing, classifying, tabulating and reorganizing the evidence to address the initial question of this inquiry (Yin, 1994). In doing this type of analysis Trochim suggests that pattern-matching (energy usage of the participants), is a most agreeable strategy for drawing a valid conclusion (Scholz & Tieje, 2002). Along with the pattern-matching technique, comparing the empirically based patterns (energy usage numbers), in combination with using these empirical numbers; utility bills over a three year period. A year by year evaluation of the study's participating residences (SB and RE) to one another was employed. The houses in this thesis were compared to each other by energy usage per square footage and then the RE to the SB. These study subjects were in turn compared to the existing governmental data, of average energy usage in a specified year, and the previous related studies afore mentioned. As is often the case, the instance of criteria (data, empirical and documentation) examined was at the discretion of the researcher for required interpretation (Tellis, 1997).

Participants

The case study "requires a comparative analysis" (Gossen, 1993, *Abstract*) of energy consumption in the use phase of RE and SB residential structures in the NoCOFR. Obviously, the greater the number of the sample size the more accurate the findings. This study consisted of six participants skewed toward SB method of construction; 5 SB, 1 RE. Initially 7 RE homes were identified and three of these were new construction and owned by a builder. Of these three, one is occupied (they responded); one is completed and unoccupied (not sold as of yet); and the other was under construction during the study period. The SB participant's homes included houses covered with a brick veneer, clapboard siding, or premium fiber cement siding.

Population

The population was selected by locating as many RE houses in the NoCOFR as possible. Based on this finding a comparable number of SB houses that were constructed in the same time period were identified. After extensive research, seven RE houses were identified by visual clues (visiting the building sites), county assessor's records, builder's website and an article in a local publication, realtor's factsheet information and letters of inquiry. In an effort to identify other RE homes, letters were sent to the residents of the neighborhoods containing known RE homes, as well as other surrounding neighborhoods, soliciting more definite information of their housing structures. Very few responses were obtained from this inquiry.

After the initial letters of inquiry; fifteen letters of solicitation, eight to SB homeowners and seven to RE (all that were identified as current residences), were sent out for volunteers to become a part of the study.   Residences that were located in or near the neighborhood that reportedly contained RE structures built by the Millers a phase of RE construction in the 1950-1960's (*see Ch. 2*) were explored first. Two of the participants are in this neighborhood (built in 1950 & 1963) and one house is not in this neighborhood (built in 1964). These are all SB built in the same era for comparison of energy consumption. These potential participants were asked to allow the investigator permission to obtain utility company usage data of their residence.

The vintage of the houses included in this study span from 1950 to 2007, not all in the same neighborhood or of the same builders. Houses built from 1990-present were used because the buildings of this era are built using more efficient construction principles and energy sensitive building codes. The newest SB home was built in 2007 and the RE constructed in 1999.

After written permission of the participants was obtained, the requisite utility company was contacted, and the utility usage data was released. The duration of the data collected was dependant on the utility company's retrieval system, the age of the house, and the length of time the current owner resided in the property.

To protect the occupants' identities, the data was codified prior to analysis. The findings are described and analyzed in charts and tables in Chapter 4. The inclusions of previous studies from global locations were then obtained and the data from these studies were compared to the results of this study to identify additional patterns. The findings in this study are communicated through the use of descriptive statistics, visual graphics and comparative text, dispersed with quantifiable billable units of the correlating numbers from utility company data.

Procedures

Utility usage data was collected for both the SB and RE buildings in Fort Collins, CO Larimer County and Greeley, CO; Weld County The information pertained to the energy consumption of the RE and SB structures. The study included a limited number of samples, only (6) agreed to participate, one RE and five SB. The homes were built between 1950 and 2007.

This study focuses on the differences in the building envelopes of the RE and SB processes by an examination of the respective utility bills for the six study objects. Note the data collected from utility companies indicated the usage of resources and not the financial economic expenditures of the occupants. This research study was dependent on the population sample of RE residences within the study boundaries, the NoCOFR.

Life Cycle

Figure 3.1, indicates that the *use phase* of a building's life-cycle is just one of the areas in which energy can be used. In most buildings, this phase is the biggest energy user and will continue to be as long as the house is occupied.

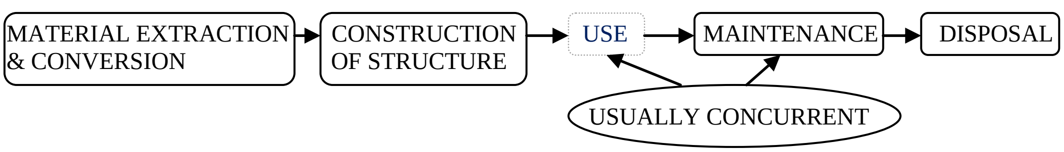

Figure 3.1 Life Cycle Phases of RE & SB Construction

The data provided by the utility companies was consolidated in a chart for analysis and comparison with data from governmental statistical sources (Department of Energy; DOE). Where needed, data from other studies was used to compare the results of the study.

The research on the energy usage of RE structures and the embodied energy expended in them is limited (Gossen, 1993). Since the study of the energy use of a RE structure is relatively new territory, determining the energy usage on an annual basis is essential to understanding the difference between this type of construction and SB homes. Several studies have looked into the amount of energy used in RE construction and found little if any data. Even the DOE Handbook of Energy Use of Building Construction lacks information on RE construction (Gossen, 1993).

Figure 3.2 graphically describes the study methodology.

Case Methodology Flow Chart

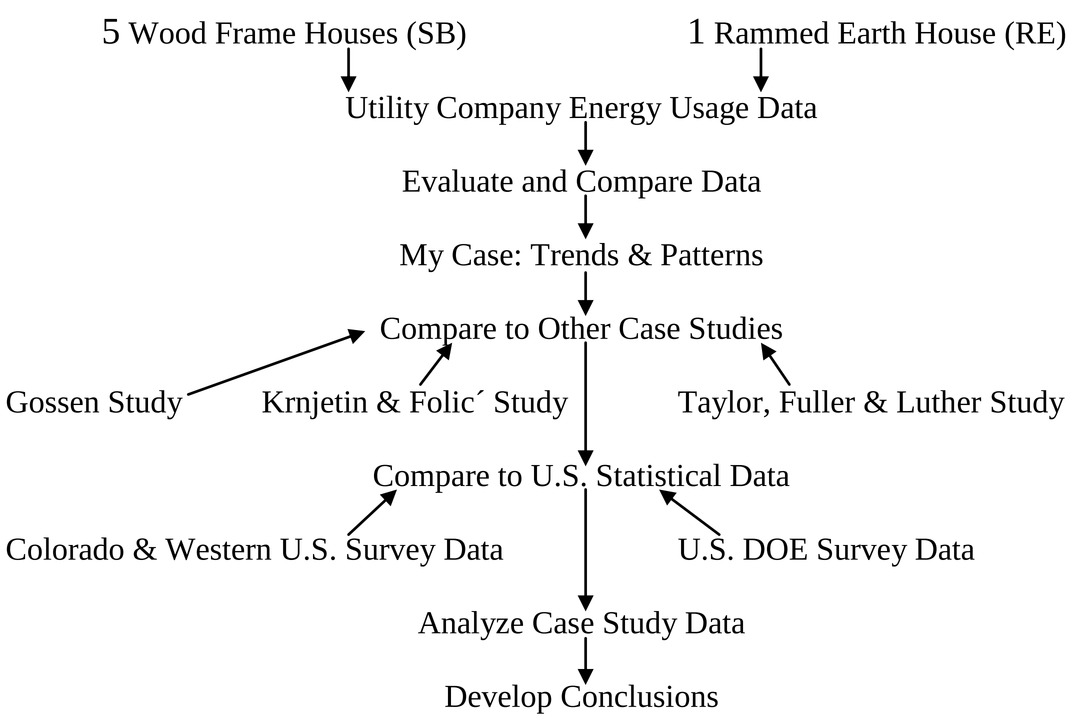

Figure 3.2 Case Study Evaluations

CHAPTER FOUR: DATA COLLECTION

The study time period is for one year for the 2007 home and for up to four years for some of the older homes. The vintage of the RE structure is 1999; the older RE residences, from 1950 to 1960. One house, built in 1977 after the OPEC oil embargo, is SB frame construction using 2x6 (more wall mass than 2x4 wall construction) in an era also considered another resurgence of RE. This house is heated with all electric heat. The wall mass is closer to that of RE and electric heat is more efficient in the fact that each room can be separately controlled. This efficiency is due to heating only the livable space when needed and isn’t necessarily determined by the mechanical system of delivery.

This range of home construction will provide a good cross section of building codes and energy efficiency requirements based on the time period the home was built. The energy consumption of the RE is comparable to the energy consumption of all SB homes in the study since the technology of RE has remained relatively stable over the period of time the SB homes were built.

Two of the responses, suspected to be constructed of RE, turned out to be of SB construction.

The locations of the Miller’s homes have not been identified and were not part of this study.

In return, the participants were promised the findings of the research. Of the fifteen potential participants, eight responded, six consented to participate and are used in this study. One resident graciously declined due to the fact the home was “all brick.” Although this information would have been useful, the wishes of the occupants were respected. Another also graciously declined, indicating the home suspected to be constructed of RE was found to be wood frame with stucco exterior cladding. In total there were six, 1 RE home owner and five SB, willing to release permission for the data collection. The heating systems most prevalent is gas heated forced air, radiant heat, while one SB home is all electric. The one all- electric heated SB home was used as another point of comparison, is included with the five SB.

The participants include;

- Wood frame of 2x6 construction, brick veneer wainscot with clapboard siding, built in 1977, 1604 SF with only electric utility.
- Wood frame of 2x4 construction, brick wainscot with premium fiber cement siding, built in 1964, 1805 SF; with natural gas & electric utility.
- RE home built in 1999, 2121 SF; with natural gas & electric utility.
- Wood frame built in 1963, 2578 SF; with natural gas & electric utility, (Hot Water radiant heat).
- Wood frame built in 2007, 1277 SF; with natural gas & electric utility.
- Wood frame and brick veneer, built in 1950, 2066 SF; with natural gas & electric utility, (Hot Water baseboard heat).

After research at the University of Northern Colorado, James A. Michener Library archives, this author re-discovered a neighborhood considered to be the original re-introduction of RE to Colorado in the 1960’s. Upon further investigation, the streets and neighborhood identified in previous research found nothing to indicate any remaining RE structures. The difficulty in identifying an RE verses a SB construction presents itself in the fact that the houses in this neighborhood are all sided externally very similarly. These houses are covered with stucco, clapboard, or plaster siding. Not one of the suspected RE structures demonstrated obvious exposed earth. Adding to the hurdle in this current research, the original builders and developers are deceased and the county assessor records doesn't delineate RE as a building material. Any structure not constructed of wood frame is considered masonry, including RE.

The first stage of this study was the collection of actual usage data from the individual occupants of the six houses in the survey and the utility companies associated with the homes. These numbers were analyzed for comparison and charted to observe the findings more clearly. The utility companies' data of each residence were then compared to the national and regional data of weather patterns, and energy consumption consensus figures.

The primary benefit of the process described is that the RE building (structure, layout and envelope) is designed to be able to maximize thermal/energy performance instead of dependence on mechanical HVAC systems. These HVAC systems are to be considered as "add-ons' to the pre-conceived design" (Bannister, Taylor, Ardren & Schmidt, 2008). The thermal capacity nature of the RE walls, ideally will lend to more energy efficiency and less dependence mechanical HVAC systems for heating and cooling.

Understanding the Numbers

The utility information includes energy consumption measured in kWh and therms. Utility usage data was then stated in a graphic format to assess what the numbers might indicate. The participant residences and type of residential structures including the exterior cladding were charted along with the HVAC systems and the square footage totals (from county assessor records).

The conversion multiplier for electricity is derived from 1kWh = 3.412= kBtu (energystar.gov). While natural gas is derived from 1ccf = 102.9= kBtu (energystar.gov). 1cf= approximately 1021 Btu's. (Can be anywhere from 1,008 to 1,034 Btu whereas there are 100 Cubic Feet per CCF or about 102,000 BTU's; 1000 Cubic Feet per MCF or about 1,020,000 BTU's and a Therm is 100,000 BTU's or just slightly less than a CCF), (Shortley & Williams, 1971).

These graphic abbreviations will be consistent throughout the graphs and charts of this study.

The average uses of electricity per month per year are clearly demonstrated in the graphics following. These numbers were computed and divided by the square footage (sf) to derive the average per sf in Tables 4.1 is the electric usage, & Table 4.2 is the Natural gas.

Table 4.1 Average Monthly Electrical Usage by Year & use/sf/yr

	Avg. monthly kWh by Yr			Avg./mo. kWh/sf by Yr		
Type	**2008**	**2007**	**2006**	**2008**	**2007**	**2006**
RE 99	577.7	520.9	604.8	3.27	2.95	3.42
SB 50	416.2	401.8	433.6	2.41	2.33	2.52
SB 63	800.2	879.9	1084.1	3.72	4.10	5.05
SB 64	948.5	921.5	764.8	6.31	6.13	5.09
SB 77	1310.7	1287.1	1337.7	9.81	9.63	10.01
SB 07	507.4	NA	NA	4.43	NA	NA

Table 4.2 Average Monthly Natural Gas Usage by Year & use/sf/yr

	Avg. monthly ccf by Yr			Avg. mo. ccf use/sf/Yr		
Type	**2008**	**2007**	**2006**	**2008**	**2007**	**2006**
RE99	63.83	73.92	66.67	0.361	0.42	0.031
SB 50	88.42	87.1	80.8	0.514	0.51	0.031
SB 63	170.83	158.2	199.3	0.795	0.74	0.928
SB 64	52.08	60.7	67.9	0.346	0.40	0.452
SB 77	0	0	0	0	0	0
SB 07	47	NA	NA	0.442	NA	NA

The average monthly total electrical and natural gas consumption was then converted to equivalent kBtu for comparison of total energy consumption by year. The total Btus consumed per year are then divided by the square footage of the house for further comparison in Table 4.3 for year 2006. The comparisons for years 2007 & 2008 are in Table 4.4 & 4.5.

Table 4.3 Comparisons of Total Energy Consumption in 2006

Type	**Total Elec. kBtu**	**Total Gas kBtu**	**Total kBtu**	**Total sf**	**Avg. kBtu/sf**
RE 99	24764.3	82320	107084.3	2121	50.5
SB 50	17752.64	99813.0	117565.6	2066	56.9
SB 63	44386.71	246033.9	290420.6	2578	112.7
SB 64	31315.34	83863.5	115178.8	1805	63.8
SB 77	54769.42	0	54769.4	1604	34.2
SB 07	NA	NA	NA	1277	NA

Table 4.4 Comparisons of Total Energy Consumption in 2007

Type	Total Elec. kBtu	Total Gas kBtu	Total kBtu	Total sf	Avg. kBtu/sf
RE 99	21328.41	91272.3	112600.7	2121	53.1
SB 50	16449.25	107530.5	123979.8	2066	60.0
SB 63	36027.31	195304.2	231331.5	2578	89.7
SB 64	37729.90	75014.1	112744.0	1805	62.5
SB 77	52698.34	0	52698.3	1604	32.85

Table 4.5 Comparisons of Total Energy Consumption in 2008

Type	Total Elec. kBtu	Total Gas kBtu	Total kBtu	Total sf	Avg. kBtu/sf
RE 99	23651.98	78821.4	102473.4	2121	48.3
SB 50	17039.53	109176.9	126216.4	2066	61.1
SB 63	32762.02	210945	243707.0	2578	94.5
SB 64	38835.38	64312.5	103147.9	1805	57.2
SB 77	53663.94	0	53663.9	1604	33.5
SB 07	19281.21	58035.6	77316.8	1277	60.6

The graph Figure 4.1, ***Yearly Energy Consumption***, compares the average kBtu/sf of each residence by year. The graphic suggests that the RE house is consistent for the three years of the study data. It might also suggest that compared to the earlier construction practices, the efficiency of energy usage has improved over the past twenty plus years. Other indicators will be discussed more in-depth in Chapter 5.

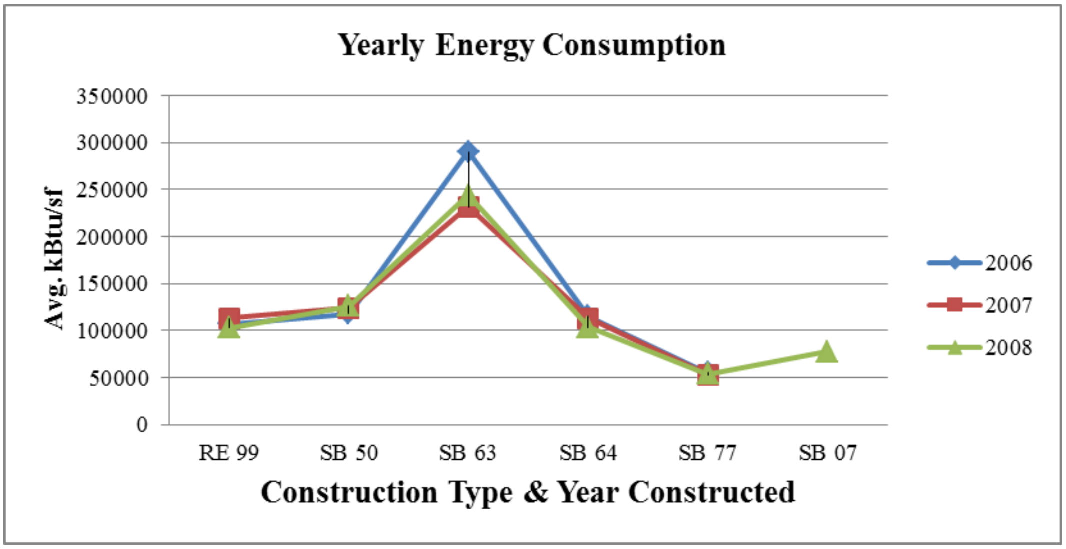

Figure 4.1 Distribution of Average Energy Consumption per Year

All the participants' natural gas usage was graphed to compare the trends of each. The assumption is made that the participants use natural gas for their heating needs in Figure 4.2.

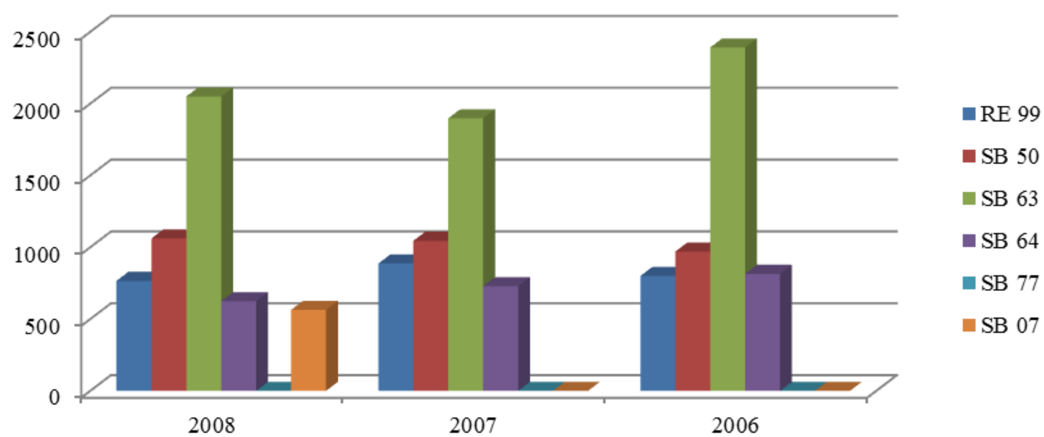

Figure 4.2 Natural Gas Total Usage of all participants

All the participants' electric usage was then graphed to comprehend the usage trends of each. The assumption is made that the participants use electricity for their cooling needs in Figure 4.3, which is a subject for future study.

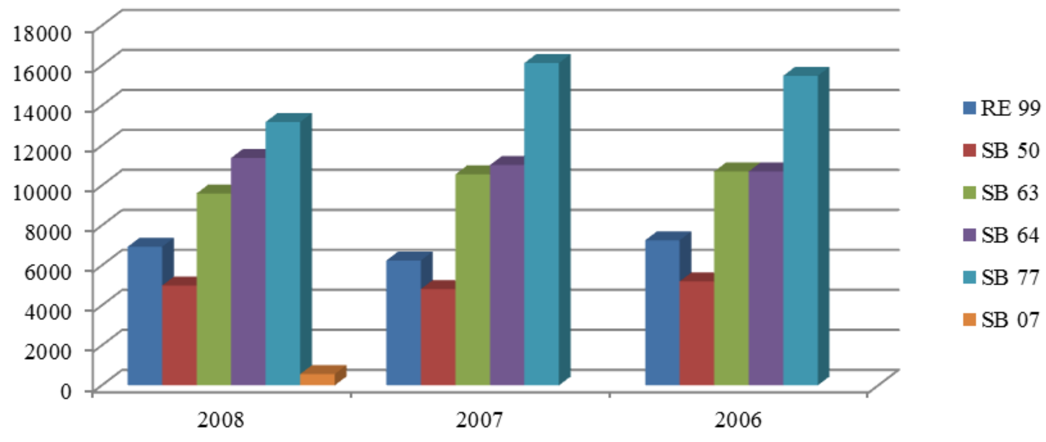

Figure 4.3 Electric Usages in kWh/yr of all participants

The comparisons of all study participants' energy consumption for heating and cooling per square foot are demonstrated in Figure 4.4.

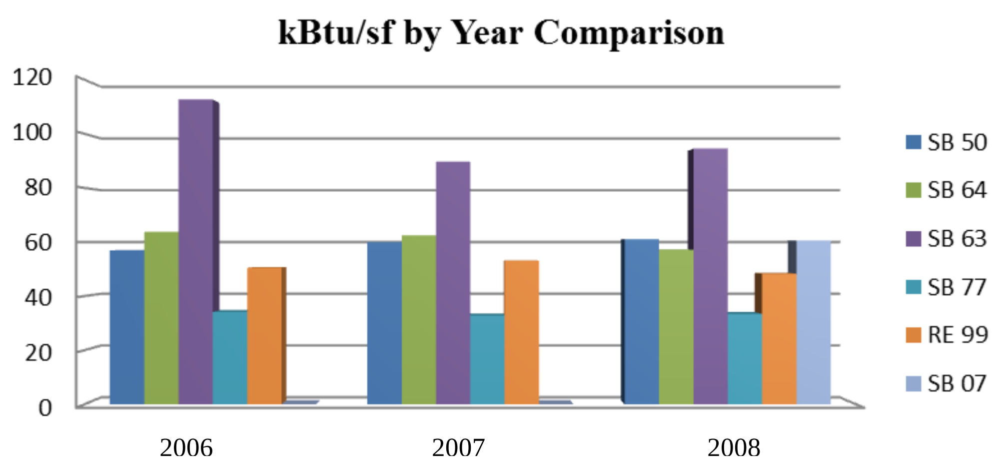

Figure 4.4 Year by Year Comparison of Study Participants Energy Consumption per square footage

Energy consumption of residence electric and/or natural gas usage of all participants are irrelevant without the common weather patterns and climate of the region to suggest reasons for the energy consumption. Figure 4.5, illustrates the average temperature in a three year time frame in northern Colorado where these homes reside.

Tables 4.6 & 4.7 are the monthly average temperatures for Fort Collins and Greeley specifically.

Table 4.6 Fort Collins Weather; Average Temperatures and Rainfall (Countrystudies.us)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Avg. High	41°	45°	51°	61°	68°	78°	85°	84°	74°	64°	50°	42°
Avg. Low	14°	18°	25°	34°	44°	51°	57°	55°	45°	35°	24°	16°
Mean	28°	32°	38°	48°	56°	66°	72°	68°	60°	50°	38°	28°
Avg. Precip.	0.4 in	0.4 in	1.4 in	1.8 in	2.7 in	1.9 in	1.8 in	1.3 in	1.3 in	1.0 in	0.7 in	0.5 in

Degrees in Fahrenheit

Table 4.7 Greeley Weather; Average Temperatures and Rainfall

(Countrystudies.us)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Avg. High	38°	45°	54°	64°	72°	82°	88°	86°	77°	66°	50°	41°
Avg. Low	12°	18°	24°	34°	44°	52°	57°	55°	45°	34°	24°	14°
Mean	26°	32°	38°	48°	58°	68°	74°	71°	62°	51°	37°	28°
Avg. Precip.	0.4 in	0.3 in	1.1 in	1.5 in	2.6 in	2.0 in	1.5 in	1.3 in	1.3 in	0.9 in	0.7 in	0.5 in

Degrees in Fahrenheit

The Analysis and synthesis of the study will be covered in-depth in Chapter Five.

CHAPTER FIVE: ANALYSIS

For the purpose of this study, the NoCOFR encompasses an area that includes the cities of Fort Collins and Greeley (Figure 5.1). Although there is much diversity in the topography, culture and history of these cities, there is a similarity in the "typical" weather, precipitation and temperature patterns. The climate of this region could be characterized by cold winters, hot dry summers, light rainfall (+1.0-+2.49"/yr), moderate to high winds, very high solar loads (300+ days of sun shine yearly), and a large diurnal temperature fluctuation (Palmer Z index, from the National Climate Data Center, NOAA, Sept. 2004).

Figure 5.1 Limits of the Northern Colorado Front Range Study Area Google Maps

National & Regional Comparisons

How does the data collection sample for the NoCOFR study compare to the average residential energy consumption of the U.S. and especially Colorado? The January 2008 report of the Southwest Energy Efficiency Project (SWEEP) (www.swenergy.org) found that 22.3% of all Colorado's primary energy consumption was used by the residential sector in 2004 (1.38 quadrillion Btu's). This total places Colorado 27th in the ranking of the United States. Electricity consumption in 2006 equated to 8,091 kWh per household and natural gas use was 56,924 cf in the state of Colorado. Colorado ranked fifteenth in natural gas & twenty-seventh in retail sales for electricity for the year 2006.

According to the Energy Information Administration of the U.S. Department of Energy's mountain division, Colorado exceeded 7,000 heating degree-days (HDD) and less than 500 cooling degree-days (CDD) in the year 2000. A degree day described by the weather service is a qualitative index to demonstrate or reflect the demand for energy to heat or cool a frequently occupied structure (www.cpc.ncep.noaa.gov, 2009).

The total number of households in the U.S. in 2001 was recorded as 107.0 million. The 107.0 million consumed 1, 139.9 billion kWh in total electricity which is an average of 10,656 kWh per household.

The 2001 Residential Energy Consumption survey indicated that the western states contributed 16.3 million households in natural gas usage to these national figures. These 16.3million households are responsible for 0.90 quadrillion Btu's, 873 billion cubic feet, 55.0 million Btu per household and 53,000 cubic feet (cf) per household. In further analyzing the consumption numbers, the west contributed to 23.3 million households using electricity. The breakdown is 0.66 quadrillion Btu, 193 billion kWh, an average of 28.3 million Btu per household and 8,287 kWh per household.

The 2005 study of this same agency subdivided the west region into the Mountain and Pacific. The Mountain division is said to include 7.6 million households with an average of 1,951 square feet (sf) of floorspace. The 2005 numbers suggest 0.68 quadrillion Btus were used which equates to 89.8 million per household or 46,000 per sf. This later study found that 10.9 million households live within the greater than 7,000 HDD climate zone. The average floorspace of these households in this mountain region increases to 2534 sf and consumes 1.29 quadrillion Btus which translates to 115.0 million Btu per household or 46.5 kBtus per sf.

The U.S. Statistical data of the number of households by year of construction is presented in Figure 5.2,

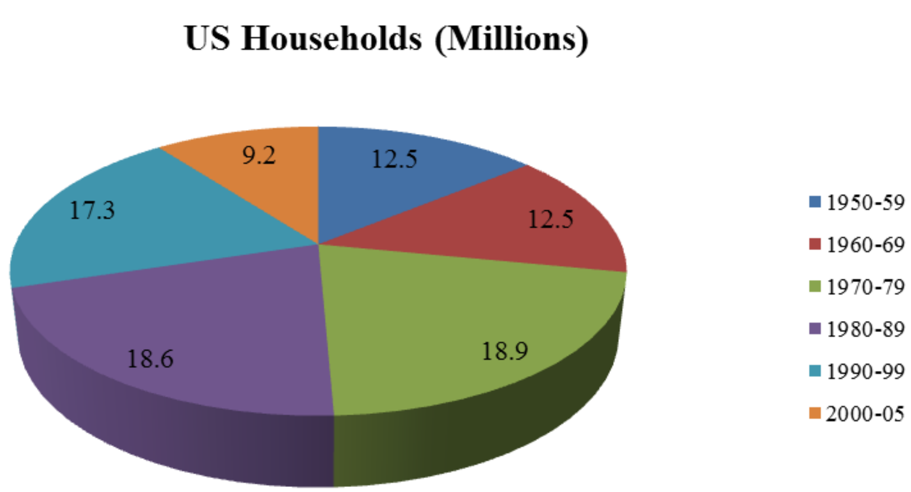

Figure 5.2 2005 Residential Energy Consumption Survey by the U.S. Department of Energy (www.doe.gov)

Table 5.1 demonstrates the breakdown of energy usage (consumption) of the average household in the United States, and then compares these consumption numbers by square footage. The energy consumption per household has remained constant from 1990-2005.

Table 5.1 2005 Residential Energy Consumption Survey by the U.S. Department of Energy (www.doe.gov)

YEAR OF CONSTRUCTION	FLOORSPACE PER HOUSEHOLD (sf)	TOTAL U.S. ENERGY CONSUMPTION (quadrillion Btu)	PER HOUSEHOLD (million Btu)	PER SQUARE FOOT (kBtu)
1950-1959	2,052	1.23	98.3	47.9
1960-1969	1,969	1.18	94.9	48.2
1970-1979	1,863	1.58	83.4	44.8
1980-1989	1,992	1.51	81.4	40.9
1990-1999	2,501	1.64	94.4	37.7
2000-2005	2,827	0.87	94.4	33.4

Values extracted from this study of the NoCOFR results were compared to the U.S. values (DOE), and the Colorado values (SWEEP, 2009). Table 5.2 compares the participating SB houses in the NoCOFR study to the NoCOFR RE house, using the RE data as a baseline model. The total kBtus per sf was compared in the amount of energy consumed more (+) or less (-) to the NoCOFR RE model. The NoCOFR SB results are compared to the RE house in the study in the column labeled Δ +/-SB & RE. The percentage of change, (increased or decreased consumption), are computed in the column labeled % of KBtu avg/sf/study yr comparing SB & RE. Again to reiterate, the SB 1977 house is an all electric heated and cooled home.

Table 5.2 Values of Thesis Energy Consumption SB verses RE

House	Area (Ft²)	Average Energy Consumption (kBtu /sf)	Δ +/- SB vs. RE (kBtu /sf)	% Δ of kBtu avg/sf/yr SB vs. RE
RE 99	2121	50.63	-	-
SB 50	2066	59.34	+8.71	117%
SB 63	2578	94.71	+44.08	187%
SB 64	1805	61.14	+10.51	121%
SB 77	1604	33.49	-17.15	66%
SB 07*	1277	60.55	9.92	120%

*1 year of energy data, whereas the rest are 3 years

Table 5.3 illustrates the heating degree days (HDD) from the Colorado Climate Zone used by U.S. Statistical Data in 2005 and a comparison to this NoCOFR study's statistical data and includes a comparison of the Western states of the U.S. The study numbers include the NoCOFR SB houses average square footage; [2066+1805+2578+1277+1604=9, 330/5=1866 sf] and the NoCOFR RE [2121sf]. The change in the area square foot (Ft² or sf) indicates above or below the average square foot (Ft² or sf) of the NoCOFR study compared to the listed averages in square foot (ft² or sf). The change of kBtu/SF in the NoCOFR study results are then compared to the listed averages of the state of Colorado and the United States totals in Table 5.3.

Table 5.3 Total Energy Values of Thesis verses the U.S., Colorado & West-US Values from the U.S. Statistical Data of 2005 (www.doe.gov).

Region	Division	Avg. Area (ft^2)	Δ+/- Area of NoCO SB (sf)	Annual Energy Consumption (kBtu /sf)	Δ+/- CO	Δ+/- US
Climate zone-CO	7.0 Thousand HDD	2534	+480 sf	46.5	-	+.5
West- US	Mtn.	1,951	+85 sf	46.0	-.5	+2.3
US	All	2,171	+305 sf	43.7	-2.8	-
(SB) study	Mtn.	1866	-	61.9	+15.4	+18.2
(RE) study	Mtn.	2121	+255 sf	50.6	+4.1	+4.6

The statistical chart (Table 5.3) is more easily visualized in a bar chart in Figure 5.3 below for further demonstration of the NoCOFR study results and the correlations to the Colorado, the western U.S. and national statistical data.

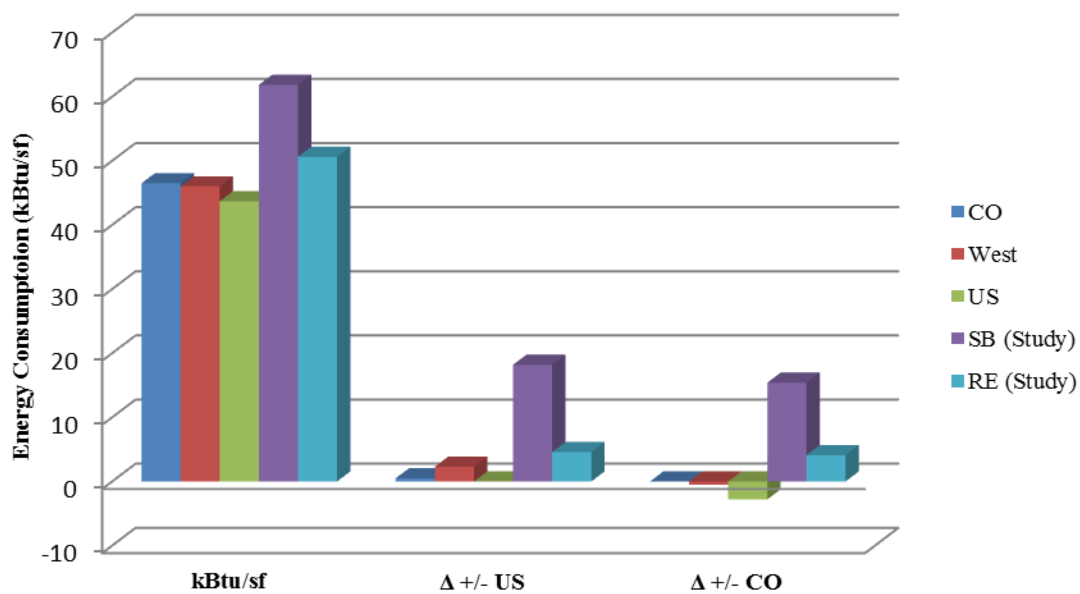

Figure 5.3 Average Annual Energy Consumption of Study Compared to the US Statistical Data (www.doe.gov)

The apparent discrepancy between the National (US) data and the Colorado (CO) data might be affected by the smaller national average home size compared to CO which has a 14.3% increase in square footage. There is an 11% difference in the square footage numbers compared to the NoCOFR study houses. The apparent discrepancy between the CO data and the NoCOFR study numbers are more difficult to ascertain. There is a 26% difference in the average square footage between the CO and NoCOFR SB and a 9.5% difference in the average square footage between CO and NoCOFR RE home. The CO square footage area is larger, yet slightly more efficient; the national numbers better the NoCOFR as well. The disparity in the comparisons might be attributed to varied micro-climatic conditions, humidity, and energy usage cultures of the residents, and density of housing in the local neighborhoods. The definition of single-family housing, (including condos and apartments) would deflate the DOE numbers. The comparative discussion in Chapter Six will shed some further light on the apparent disparity of these percentages.

A paper presented by Krnjetin and Folic′ may support the inconclusive limited findings of this research. Using raw earth can significantly contribute to the lower total energy consumption during the use phase and is just a part of the conclusion of Krnjetin & Folic′ (Krnjetin & Folic, 2002).

Their collaborative study in Serbia and Montenegro indicates that a contemporary building (SB) consumes an estimated average of 250 kWh per m^2 [23.2 kWh/sf or 79.2 kBtu/sf] per year to maintain a comfortable temperature. Comparatively, while the most energy efficient structures of RE have an expected annual consumption of 130kWh/m^2

[12.1 kWh/sf or 41.3 kBtu/sf] (Krnjetin & Folic′, 2002). In Germany, RE houses constructed by the end of the twentieth century (1999) expend around 77-95 kWh/m²[7.2-8.8 kWh/sf or 24.6-30.0 kBtu/sf]. The projected calculations of this study suggests that a contemporary home of 120m² **[1**20 square meters is equal to 1,291.67 square feet] consumes about 30,000 kW/h (102360 kBtus) annually, while the RE homes are projected to consume 15,600kW/h (53227.2 kBtus) of energy annually (Krnjetin & Folic′, 2002). Figure 5.4 graphically depicts the claim of 30%-50% energy savings. The NoCOFR RE structure measured favorably with all comparisons in this research and that of the studies of Krnjetin and Folic′ in 2002.

These comparative results of multiple studies are illustrated in Fig. 5.4.

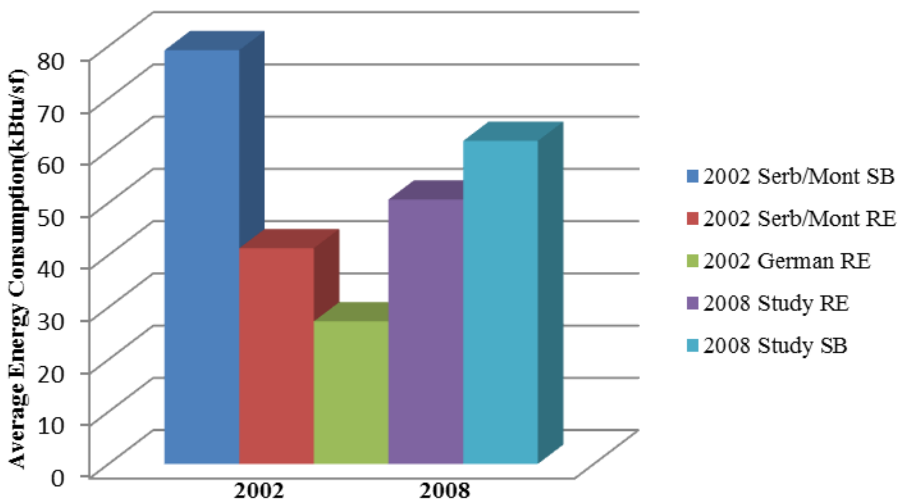

Figure 5.4 Comparison of Average Energy Consumption from Multiple Studies (Note: 1sf=0.092903 m²)

The projected energy consumption data for the year 2002 are depicted in graphic format in Figure 5.5 for the SB and RE participants of the Serb/Montenegro study. This particular study suggests that RE structures consumed less energy and were expected to consume significantly less energy (up to 50%) to heat or cool the houses.

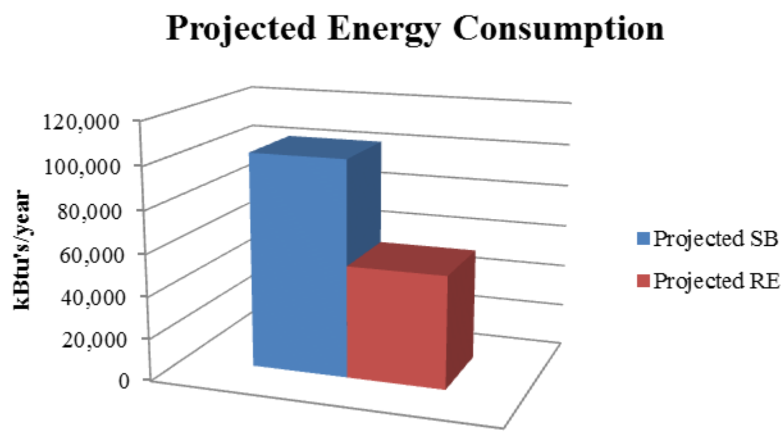

Figure 5.5 Projections of Energy Consumption per Year (2002) Graphic produced by author based on findings of Krnjetin & Folic′. It should be noted that 120m² is approximated to 1,291.67 sf.

The work of Krnjetin and Folic′ had more favorable results (up to 50%), than this NoCOFR study which obtained a lesser result. The comparative discussion in Chapter Six will shed some further light on the apparent disparity of these percentages.

CHAPTER SIX: SUMMARY AND FUTURE RESEARCH

In order to understand the data compared with results of other studies that used other previously developed theories. These theories, such as that of the properties of thermal dynamics are used in conjunction with comparisons of the research studies in Arizona (Gossen, 1993), Montenegro (Krnjetin & Folic′, 2002) and England (Taylor, Fuller & Luther, 2007), to solidify the constructs of this thesis. This mixture of concepts were then used to assess the commonalities and differences of RE and SB construction with respect to their energy consumption. These studies referred to above, each in a different locale, climate and each using a slightly different approach, reached a similar conclusion using a larger sample size; the RE houses performed more efficiently than SB construction methods.

The findings of these studies expose an element that is not fully understood-the capabilities of thermal properties inherent in earthen wall structures. The potential uses of thermal dynamic materials in RE walls are not fully explored. The current practice used in contemporary building construction demonstrates a lack of understanding of the flywheel phenomenon. A second concern is builders apparently build RE houses in the same manner as the SB houses. That is to say they operate on the premise that the RE house is constructed much like that of SB house. RE walls are constructed, they are insulated and then an exterior wall covering is attached. The RE houses located in the Northern Colorado Front Range (many whose occupants for whatever reason, chose not to be included in this study), used wall systems believed to be constructed of earthen materials then covered in clapboard siding or stucco. Thirdly, when designing a HVAC system for the RE home, is it the same system typically used in SB construction? This design assumes that all the characteristics of the two buildings are the same; an assumption that would not take full advantage of the RE wall natural properties. If the properties of RE houses are not used fully to the natural capacity, due to the added layers of protection and the improper use of HVAC operating systems, one may surmise the energy use numbers used in this study may decrease for a well designed and used RE home. This leads to the question: Does the lack of RE construction traditions in the United States inhibit achievement of the reported energy savings by the European studies of similar structures?

Conclusion

Based on the low response rate of RE home owners this type of study cannot be performed in an area where the RE is an anomaly method of construction. The small response rate of RE owners makes the findings of this particular study inconclusive. Other studies should include a wider geographic area and use heating and cooling degree day adjustments to compensate for the differences in geographic areas. This would strengthen future studies and provide for the inclusion of other studies from around the world if heating and cooling degree data is available.

Owner lack of education about the type of home they lived in coupled with public records that identified potential RE homes as masonry, appear to be two of the main reasons for the small number, 6, of RE homes that were identified. The lack of homeowner education also may increase the misconceptions regarding this “non-traditional” construction method for residential housing. In addition, the lack of understanding concerning the attributes of a RE home may render useless the mass in the walls to offset heating and cooling costs as indicated by the results of this study.

Even with the limitations of the study there are several important findings from the research. The first is the need to better educate homeowners about the type of home they live in and how the systems of the home operate so efficiency in heating and cooling can be achieved. Second is the education needed for RE to once again become an acceptable method of home construction. In the last one hundred years in the United States alone, RE construction had at least four revivals; 1920-1930; 1940-1950; 1970-1980 & the late 1990's until the present. The current RE construction methods are driving a small resurgence in this building method as evidenced by the fact that 3 of the 7 RE homes identified were builder owned.

Other important attributes of the RE home may include lower overall life cycle costs, in all phases of the homes life; material extraction, construction, use/maintenance, and disposal. Consumers need to be educated about RE resistance to fire, earthquakes, pests, the thermal and insulation characteristics, and the ease in which the earth is reclaimed once the building becomes obsolete. All of this information impacts the total environmental cost of the structure, RE or SB.

In both building systems the environmental impacts, specifically in the *use phase* of the life cycle can be calculated in the forms of energy consumption, the amount of waste generated, the depletion natural resource, and damage to the ecosystem (*see* Sha, Deng & Cui, 2000). Gossen estimated that SB construction, in that phase alone, would consume approximately 12,236 kWh annually or 125,284,404 Btu, which is equivalent to 5.67 tons of coal per year (1993).

Future Research

Future research needs to include a wider spectrum of RE and SB structures in a greater geographic area to be more conclusive. RE is grabbing a small hold as an option in new home construction, mostly in Arizona and California in the United States and more widely in Australia. This resurgence will provide better data for the current consumption of resources for heating and cooling based on the use of the latest HVAC technologies and understanding of the performance of the building envelope.

In addition the usage habits of the participants need to be studied to determine the impact they have on the outcomes shown by the analysis of the utility data alone. It may be necessary to build 2 identical structures and let them operate without occupants for a year to create a baseline for RE homes in a region prior to completing a thorough study of RE verses SB homes in that area.

The results of this study indicate the methods used for this study are viable although a more controlled study is required to obtain results that may be generalized to the population of RE homes in a geographic region.

Other topics for future study and research could possibly include:

- The claims of earthquake resistant structures made from earthen materials might be explored by creating a scale model of RE tested on a shake table.
- The impacts of the two building systems during the construction phase and an overall life cycle cost of the two systems.

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Further Suggested Readings

The Natural Building Network - find natural builders, teachers and resources.

Earth Architecture - A website whose focus is contemporary issues in earth architecture.

Rammed Earth - The Australian Connection - A good description by an owner-builder can be found at this Australian Rammed Earth site

Do it Yourself Rammed Earth - Journal of father & son building rammed earth home in Dallas

Rammed Earth in Canada - A good overall rammed earth site

Historic Rammed Earth - A good site about the history of rammed earth throughout the world, and research into preservation techniques

Stabilized and Insulated Rammed Earth - The first rammed earth builder to build insulated rammed earth buildings that are earthquake engineered.

Simmonds Mills - A UK architecture and building company using unstabilized rammed earth construction.

Earth Architecture by Ronald Rael © 2009 Published by Princeton Architectural Press, NY., NY

APPENDIX A

H 100 approval process

Title of study:

Energy Consumption in the Use Phase of Residential Housing: a Comparison of Wood frame & Rammed Earth Construction in the Northern Colorado Front Range

Principal investigator: *Brian Dunbar*
970.491.5041
dunbar@cahs.colostate.edu

Co-principal investigator: *Kirk E. Jensen*
970.491.7692
kejensen@cahs.colostate.edu

Why am I being invited to take part in this research?

In order to facilitate the completion of this thesis, utility company information on energy consumption for comparable sized wood frame and rammed earth residential structures is necessary. The owner's permission is required for the release of utility records. The findings of this study, pertaining to the residence of the occupants, shall be made available to the owner's for understanding their energy usage. Suggestions of energy savings may also be available to the owner's upon request.

Who is doing the study?
Kirk Jensen is collecting data for self funded research to complete his thesis for a Master of Science degree in Construction Management.

What is the purpose of this study?
The purpose of this research is to examine the similarities and differences between common wood frame construction and the traditional rammed earth construction practices and how these processes are evaluated in terms of energy consumption in heating and cooling.

Where is the study going to take place and how long will it last?

The current and existing rammed earth residences are located in Weld County, Colorado. The intent of the study is expected to be completed in 2008.

Page 1 of 3 Participant's initials _______ Date _______

What will I be asked to do?
Residents of rammed earth on the study area are asked to provide their permission to obtain the necessary utility company energy usage data for their residence. The owner's name and information pertinent will be coded in any publication to protect the private lives of the participants.

Are there reasons why I should not take part in this study?
There are no known reasons and detrimental effects or risks.

What are the possible risks and discomforts?
It is not possible to identify all potential risks in research procedures, but the researcher(s) have taken reasonable safeguards to minimize any known and potential, but unknown, risks.

Are there any benefits from taking part in this study?
The findings of this research shall only enhance the owner's ability to conserve energy consumption and save on utility expenses. The benefits to the society as a whole will be a more sustainable building environment and a decreased level of CO^2 *and related greenhouse gases. A reduction in the eco-footprint is hoped for.*

Do I have to take part in the study?
Your participation in this research is voluntary. If you decide to participate in the study, you may withdraw your consent and stop participating at any time without penalty or loss of benefits to which you are otherwise entitled.

What will it cost me to participate?
The only costs associated with my research study and resident's participation is time. There isn't any financial burden to participate.

Who will see the information that I give?
I will keep private all research records that identify you, to the extent allowed by law. Your information will be combined with information from other people taking part in the study. When I write about the study to share it with other researchers, I will write about the combined information I have gathered. You will not be identified in these written materials. We may publish the results of this study; however, we will keep your name and other identifying information private. I am collecting only utility company energy consumption data pertaining to specific residential structures.
This study of residential energy consumption will permit the residents information to be anonymous to all accept the researcher (myself). For published data, the respondent's information will be coded using identifiers. This code will resemble the mapping coordinates used by maps to locate addresses. An example; The ABC family living at 123 Any Street, Anywhere; will be coded "A5".
Page 2 of 3 Participant's initials _______ Date _______

The alphabet will be used along one axis of a map and the numerical will be used along the opposing perpendicular facing axis. I will make every effort to prevent anyone who is not on the research committee from knowing that you gave me information, or what that information is. For example, your name will be kept separate from your research records and these two things will be stored in different places under lock and key. You should know, however, that there are some circumstances in which we may have to show your information to other people. For example, the utility/ energy companies require me to show your name and address along with your written permission and residence information for me to retrieve their records about your residence.

Can my taking part in the study end early?

Permission as well as name and address information from participants to retrieve utility information is all that is needed. There will be no need to continue taking part once voluntary information is supplied from the residents to release utility company records.

Will I receive any compensation for taking part in this study?

My gratitude and copies of energy consumption information requested for any future applicable energy saving actions by the home owner.

What happens if I am injured because of the research?

There will be no physical involvement by participants other than their signature and permission to retrieve utility usage data.

The Colorado Governmental Immunity Act determines and may limit Colorado State University's legal responsibility if an injury happens because of this study. Claims against the University must be filed within 180 days of the injury.

What if I have questions?

Before you decide whether to accept this invitation to take part in the study, please ask any questions that might come to mind now. Later, if you have questions about the study, you can contact the co-principle investigator, Kirk E. Jensen at 970.491. 7692. Or you may email at kejensen@*cahs*.colostate.edu. *If you have any questions about your rights as a volunteer in this research, contact Janell Barker, Human Research Administrator at 970-491-1655. We will give you a copy of this consent form to take with you.*

Your signature acknowledges that you have read the information stated and willingly sign this consent form. Your signature also acknowledges that you have received, on the date signed, a copy of this document containing 3 pages.

____
Signature of person agreeing to take part in the study

____
Date

____
Printed name of person agreeing to take part in the study

____
Name of person (Researcher) providing information to participant

____
Date

____
Signature of Researcher

Page _3_ of _3_ Participant's initials _______ Date _______

Institutional Review Board Determination Notice
Protocol title: Energy Consumption in the Use Phase of Residential Housing: A Comparison of Wood Frame and Rammed Earth Construction in the High Plains Region

PI: Brian Dunbar, Construction Management
Co-PI: Kirk Jensen, Construction Management
Review date June 5, 2008
Notification date June 6, 2008
Type of review INITIAL (expedite review)
Review of the information you provided resulted in the following determination:
Please provide more details or clarification to the following H-100 questions:

Describe the consent process and method of consent to be used. In addition to using a signed consent form, how will the research be presented to the potential participants? Will it be a cold call by knocking on each door and introducing the study? Will the cover letter be given to them and then the consent form or will the cover letter be sent ahead of time?
The cover letter will be sent ahead of time, then the consent form. If the chance arises that I contact someone cold; the script may proceed as follows: Hello! My name is Kirk Jensen; I am a graduate student at Colorado State University studying Construction Management. I am conducting a study of rammed earth construction and the associated energy efficiencies compared to the standard wood framed housing

structure. Would you be interested in participating in my study? If yes; present cover letter for further information & consent form. If not; "Thank you very much for your time and consideration".

How will subjects be recruited and where will the recruitment take place? The response indicates where and what criteria will be used, but it doesn't address how people will be asked to participate in the research. Please provide a recruitment script that will be used. If the researcher will approach each home individually, please submit a sample script that will be used when introducing the study to the participants and asking them for their participation. Include who the researcher is, that it is CSU sponsored research, what the purpose of the research is, what is being asked of the participant and that participation is voluntary. As a sample closure to the script, you would add, ***"If they agree to hear more about the research, a cover letter is given for them to read and then the consent form to sign and read."***

a. As a side note, I'm not sure you need all of the documents that you presented. Since we are unclear about what all will be done, if you are going door-to-door and recruiting homeowners, you would just need a verbal recruitment script as mentioned above. And if the participants are interested, then you provide them the consent form. Unless both are needed, please describe how the cover letter and consent form will be used and presented to the potential participants. Please make the recruitment script in "you" format – instead of using "the participants". If the cover letter will still be used, change it to "you" format as well.

Recruiting homeowners will be done by selecting those persons that live in a rammed earth house. The cover letter will be sent to introduce the project and those interested participants will then be provided a consent form.

If secondary data analysis is being conducted, please describe the original consent procedures. The response did not address if records or data was being accessed or analyzed in the study. From the H-100, it is understood that records will be accessed from the utility companies. That data is already available and would be considered secondary. So, the response should be something similar to" Secondary data will be accessed from the utility companies with each person's permission. Current consent is being obtained to access the secondary data records."
The records from the utility companies will be used in the study, then they will be analyzed to ascertain the structures energy efficiency and associated carbon footprint. The secondary data will be used to construct a matrix to describe the energy consumption per square foot of each particular structure. The rammed earth constructed house will be compared to the wood frame house, built in the same vintage and approximate locale. " Secondary data will be accessed from the utility companies with each person's permission. Current consent is being obtained to access the secondary data records."

How Many Subjects do you Plan to Study? For this question, are you only going to a maximum of 5 home owners? Please confirm.
There are only 8 known rammed earth structures in Northern Colorado; I have identified the neighborhoods of the (5) oldest structures. They are located on a street with only a dozen homes on the street. I will need to determine which houses are of rammed earth construction. All residents on that street shall receive the cover letter, unless more detailed county records can be obtained. The others in the study will be houses constructed of wood frames within the same time period, possibly those on that same street as well.
The H-100 only indicates that the researcher is going to each house to ask permission for access to the homeowners utility use, but the email that was sent with the consent form indicates that there will be an oral interview – will questions be asked or are you referring to the verbal introduction of the research and asking the homeowner for permission to access their utility usage? Please briefly describe and confirm the process from how the participants will be approached to how the PI will access the utility records.
I am referring to the verbal introduction of the research and asking the homeowner for permission to access their utility usage. After receiving the owner's permission, recorded on the utility company form, each company has their own, the utility company will turn over that particular addresses utility energy consumption data for the duration of 1-10 years. Or as far back as the utility company data base will allow.
As a suggestion, you may want to provide a line on the consent form for the participant to write down their address or how will that be documented with their consent?

Consent to Participate in a Research Study
Colorado State University

APPENDIX B

Sample letter to participants

September 23, 2008

Dear (Name of Participant);

I am writing this letter by way of introduction; my name is Kirk E. Jensen. I am a graduate student studying Construction Management at Colorado State University. My graduate study and entitled Master's thesis; is the Energy Consumption in the Use Phase of Residential Housing: a Comparison of Wood frame & Rammed Earth Construction in the High Plains Region.

The purpose of my writing to you is I believe you reside in a rammed earth residential structure home, and I would like to invite you to participate in my study. The premise of this research is to examine the similarities and differences between common wood frame construction and the traditional rammed earth construction practices; and how these processes are evaluated in terms of energy consumption in heating and cooling. Participation in my study will not involve any risk or sacrifice on your part. Those of you who are willing to be a part of my data collection portion of this current research requires only your permission and signature on a standard utility company document to release their records of energy consumption in measurable units (Btu's or kWh) for your residence. There will not be disclosed any documentation of the economics of your utility bill. The possible timeframe will be for the past 3, 5 up to 10 years or dates available from the utility company.

Your name and pertinent information will be coded in any publication to protect your privacy. In order to facilitate the completion of the thesis, utility company information on energy consumption for comparable sized wood frame and rammed earth residential structures is necessary. Your permission is required for the release of energy consumption information on your utility records. The findings of this study, pertaining to your residence, shall be made available to you for understanding your particular energy usage. Suggestions of energy savings may also be available to you upon request.

Please accept this letter as an expression of my genuine interest in pursuing an opportunity to discuss my study and the findings with you in the near future. Thank you for taking the time to respond to this letter with the enclosed envelope or by fax at the number above on or before October 10, 2008. If you have any questions please feel free to contact me at 970.491.7692 or email at kejensen@colostate.edu.

Sincerely,

Kirk E. Jensen

APPENDIX C

Sample letter to utility companies

November 25, 2008

Dear Administrator;

I am writing this letter by way of introduction; my name is Kirk E. Jensen. I am a graduate student studying Construction Management at Colorado State University. My graduate study and entitled Master's thesis;

Energy Consumption in the Use Phase of Residential Housing: a Comparison of Wood frame & Rammed Earth Construction in the High Plains Region.

The purpose of my writing to you is I have collected permission letters from some of your customers (see enclosed) with the intent to have released to me their records of energy consumption in measurable units (Btu's, CFC's or kWh) for their residence information from you. The premise of this research is to examine the similarities and differences between common wood frame construction and the traditional rammed earth construction practices; and how these processes are evaluated in terms of energy consumption in heating and cooling. Please do not disclose to me any documentation of the economics of their utility bill. The timeframe I am interested in is a minimum of one year to a maximum of 10 years or the dates available from your utility company.

In order to facilitate the completion of the thesis, utility company information on energy consumption for comparable sized wood frame and rammed earth residential structures is necessary. I have received written permission required for the release of energy consumption information on utility records. The phone numbers of the willing participants are included in this correspondence, should you need to verify their authenticity. The findings of this study, pertaining to the residences, shall be made available to the participants for understanding their particular energy usage.

Could you please include any information on average usage data that you might have for residences in the High Plains region.

Thank you for taking the time to respond to this letter; electronically by email, with the enclosed envelope or by fax at the number above on or before December 15, 2008. If you have any questions please feel free to contact me at 970.491.7692 or email at kejensen@colostate.edu.

Sincerely,

Kirk E. Jensen