Assessing Cost-Effective Energy Savings on Joint Base Lewis-McChord Housing

by

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A thesis submitted in partial fulfillment
of the requirements for the degree
Master of Environmental Studies
The Evergreen State College
July 20th, 2012

This Thesis for the Master of Environmental Study Degree

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ABSTRACT

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The study focuses on six existing communities consisting of typical site-built single and multi-family houses constructed between 1930 to the mid 1980's with an additional, newer modular multifamily Energy Star®/Building America community, built in 2005-08. These military family housing communities are located at Joint Base Lewis-McChord (JBLM). The study employs utility billing analysis and technical field research to assess baseline energy efficiency while utilizing the predictive functions of the modeling program BEopt.

Utility billing analysis compares the electric, gas and total annual energy use within the communities, providing consumption data separated into gas and electric base-loads for each community, water heater fuel type, and heating/cooling loads. Energy modeling programs estimate energy consumption for proposed retrofit measures and assess the potential gains in energy efficiency available (through retrofit measures) in each of these communities. Field visits to these communities provided critical data on air leakage rates and other physical characteristics of importance in the energy modeling. Using all three approaches, those retrofit measures yielding the greatest energy savings for the lowest cost are identified. These measures include: 1) improving HVAC ductwork on existing 90% AFUE gas furnaces 2) building envelope air sealing and installation of ASHRAE 62.2 compliant ventilation systems where needed, 3) ceiling insulation R15 to R49, and 4) conversion of tank water heaters to tankless gas condensing water heaters at existing water heater wear-out.

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Abbreviations

ACH_{50}- Air Change Rate at 50 Pascals pressure

ALA- Associated leakage area

ASRE- American Society of Refrigerating Engineers

Btu- British thermal units

CFM_{50}- Cubic Feet per Minute at 50 Pascals

CFL- Compact Fluorescent Light

DHW- Domestic Hot Water

DoD- Department of Defense

EIA- Energy Information Administration

EQR- Equity Residential

JBLM - Joint Base Lewis-McChord

kWh- Kilowatt-hour

MWh- Megawatt-hour

MVR- Minimum Ventilation Requirement

NBS- National Bureau of Standards

NIST- National Institute of Standards and Technology

NPCC - Northwest Power and Conservation Council

Quad- Quadrillion British thermal units

REE- residential energy efficiency

Acknowledgements

There are many people who offered knowledge and experience, time, patience, and guidance. Principal among them are Mike Lubliner, Luke Howard, Ken Ecklund, and Rick Kunckle at the Washington State University Energy Program; Mike Greer at Equity Residential; and from The Evergreen State College, Rob Knapp and Ralph Murphy. Offering endless support, insight, humor, and a sympathetic choir to vent at are my colleagues in the Master of Environmental Studies, my family, and my friends.

“Our ignorance is not so great as our failure to use what we know”

-Dr. M. King Hubbert

1. INTRODUCTION

1.1 Introduction and Objective

The U.S. consumes roughly 25% of the world's resources, chief among those resources are materials used to generate electricity. E. F Schumacher, author of *Small is Beautiful*, puzzled over our treatment of these resources as capital, and reflected on our usage of these materials as if they are renewable resources when in fact these materials are not. The combustion of fossil fuels, such oil, coal, and natural gas (for the purpose of electricity generation) produces staggering quantities of greenhouse gases. Plastic, a product of petroleum, has become an indispensable element in everyday life and is non-biodegradable, hazardous to wildlife, and is recyclable only in part. As it is only a matter of time until they become scarce, the wisdom in consuming finite fossil fuels and fissile minerals to supply our country with energy is questionable at best.[1]

Stream lining our methods of energy production is one method to reduce non-renewable resource consumption, but reducing consumption possesses far greater potential. Within the realm of residential housing and construction some of the most effective steps toward energy conservation are measures used to reduce air leakage from building envelopes, increase insulation, upgrade appliances to energy efficient models when the opportunity presents itself, and to educate those who consume energy and those who generate energy.

In many respects, education is the most effective of the listed methods of energy waste reduction. However, effecting change on people's behavior and habits is notoriously difficult as there are numerous factors contributing toward those behaviors. For example, if one reduces air leakage within a building, conditioned air (meaning air artificially heated or cooled) will remain inside thereby reducing the need to run the furnace/AC (to match the occupant's desired comfort settings). If measures are taken to reduce air leakage within the building of a low-income family, a family could afford to maintain the space at a comfortable thermostat setting as opposed to heating the space according to

[1] Fissile materials, such as uranium, used to fuel nuclear fission reactors.

affordability. This situation yields little to no reduction in energy consumption, but aids the family in maintaining a comfortable lifestyle.

Of equal if not greater importance are the effects of reducing energy consumption on our health (as a nation of individuals and as a society) and on our environment. Reducing energy consumption increases environmental health by reducing tailings and other toxic by-products of fuel extraction, reducing byproducts of electricity generation, and reducing waste generated in the transportation of fuel from source to site, to name a few.[2] Reducing the usage of nuclear fission reduces the radioactive (toxic) byproduct of fission and reduces the distortion of the natural temperature and operations of the water source necessary to cool the reactor. Lowering fossil fuel consumption reduces greenhouse gas emissions such as carbon dioxide, sulfur dioxide, and methane produced during fossil fuel combustion. Other benefits include a reduction in the volume of particulate matter (particle-sized organic residuals of combustion) where the greater the organic matter content, the more particulates are released. Particulate matter directly impacts respiratory functions and often contains small amounts of toxic heavy metals such as mercury.[3]

Finally, increasing energy efficiency addresses the issue of waste. When measures to increase household efficiency are available, yet not implemented, energy is needlessly consumed. We expend the resources, the time, effort, money, and stress required to extract and process fuel, and to produce energy, only to waste it. This system is built upon the premise that fuel is abundant to the degree of being inexhaustible.

The goal of this study was to conduct research into energy consumption on Joint Base Lewis McChord in order to ascertain energy efficiency among houses

[2] In this instance, transportation is a term encompassing the refined fuel used during the extraction of the raw fuel as well as the transportation of that fuel, once extracted. It also embraces the impact of heavy machinery on the location of fuel extraction. In order to extract raw, unprocessed fuel such as oil, a derrick, drill pipe, generators, living quarters and supplies for crews operating the machinery must be transported to the drilling site. Once established, a constant stream of support vehicles carrying water, refined fuel for the generators, and additional equipment and incidental supplies is required to sustain the extraction process.
[3] Heavy metals such as mercury do not exit the body meaning the greater the exposure, the greater the accumulation of said metal in the body.

located on the base and identify retrofit measures with the greatest reduction in energy consumption at the lowest cost using a combination of field testing, utility billing analysis, and energy modeling programs. In addition to this primary direction of study, research will also be conducted into the energy efficiency of high efficiency tankless natural gas hot water heaters as compared against power-vented standard natural gas water heaters.

1.2 Defining Energy

Energy can be described in many ways, some involving mystical properties and some philosophical elements. For the purposes of this paper, energy describes the potential to perform work and it is energy in the form of electricity and heat is the focus. In the U.S., electricity is the most common form of energy used and is produced from a variety of sources including the combustion of fossil fuel, nuclear fission, and hydroelectric, among others. As an end-product, heat is used primarily to heat buildings and water.

In describing energy production, transmission, and consumption, it is important to differentiate site energy from primary energy. The U.S. Energy Information Administration (EIA) defines site energy as “energy directly consumed by end users” versus primary energy, defined as “site energy plus the energy consumed in the production and delivery of energy products” (EIA, 2011). While the EIA articulates the difference between the two quite well, an alternative differentiation considers site energy as a household and all the appliances, Heating Ventilation and Air Conditioning (HVAC), entertainment options, etc. contained therein; source energy considers the machinery and equipment necessary to extract and process the energy (mining, drilling, refining, etc.) as well as the process of transporting the energy. This latter assessment of site versus primary energy is particularly applicable as this report focuses on residential energy consumption.

1.3 Generation and Transmission of Energy

Energy generation occurs in a variety of ways, ranging from fossil fuels to nuclear, to solar and wind, to geothermal, hydro, and biofuels. While the dominant sources vary from location to location, on a national level (in 2010) coal delivered 21.05 quadrillion Btus (quads) of energy, natural gas supplied 24.45 quads, renewable[4] produced 5.74 quads, and liquid fuels (petroleum-based) provided the U.S. with 36.96 quads of energy (EIA, 2011).[5] When alternative measures such as energy efficiency exist yet are not utilized, non-renewable resources such as fossil fuels are needlessly wasted.

At present, we not only rely heavily on fossil fuels for energy production but also use petroleum in hundreds of different applications. The Texas Alliance of Energy Producers list roughly 480 different uses for petroleum; while many are simply different end products within a given industry (such as textiles) the following excerpt provides an example of material breadth: “typewriter keys; wire insulation; desk organizers; fake furs; T-shirts; electric scissors; golf bags, skin conditioners; photographs; (outdoor) carpeting” (Texas Alliance of Energy Producers, 2012). With so many products derived from petroleum, it would behoove us, certainly as a nation if not a world, to reduce our consumption of petrol for the production of energy[6].

Once generated, electricity is transmitted from the source location to its final destination through a network of cables and lines collectively known as the grid. The grid is composed of many different elements ranging from high voltage transmission lines used as conduits for electricity, to transformer stations used to

[4] “Includes conventional hydroelectric, geothermal, wood and wood waste, biogenic municipal waste, other biomas, wind, photovoltaic, and solar thermal sources” (EIA, 2011).

[5] Btu stands for British Thermal Unit and is one of the most common measurements of energy generation and consumption. One Btu is equivalent to the heat released by burning one kitchen match; one kilowatt hour has 3412 Btus, one barrel of crude oil possesses 5,800,0000 Btus, one cubic foot of gas contains between 1,008 to 1,034 Btus (http://www.uwsp.edu). America produced 72,970,019 billion Btu in 2009 yet consumed 94,578,267 billion Btus (http://www.eia.doe.gov/totalenergy/annual.cfm#summary). In order to close the gap between generated and consumed, we import oil, 22,849,185 billion Btus worth. In 2009, the U.S. released 5,424.53 million metric tons of $CO_{2\,f}$ from the combustion of fossil fuels.

[6] It also behooves to reduce our consumption of materials and products that have little to no value and are quickly discarded. Or, in the case of packaging material, immediately discarded.

increase and decrease the voltage of long distance electricity transmission (and thereby the efficiency of transmission), to the power lines running to a house. During the transmission and distribution of electricity, a percentage of the electric current is lost as function of resistance (the metal cable is not a perfect conductor) and through inefficiencies in other transmission equipment[7]. In a publication entitled "Energy Efficiency in the Power Grid", ABB Inc. describes transmission loss thusly:

> *According to data from the Energy Information Administration, net generation in the US came to over 3.9 billion megawatt hours (MWh) in 2005 while retail power sales during that year were about 3.6 billion MWh. T&D losses amounted to 239 million MWh, or 6.1% of net generation. Multiplying that number by the national average retail price of electricity for 2005, we can estimate those losses came at a cost to the US economy of just under $19.5 billion.*

An additional and succinct perspective comes from the EIA: "The losses in the generation, transmission, and distribution of electricity are more than twice the amount of electricity delivered to the household" (EIA, 2011). Reduce the need for energy and the loss in transmission is reduced as well.

1.4 Residential Energy Consumption, Efficiency, and Conservation

1.4.1 National

When electricity reaches its destination, a single-story site-built house for example, it is consumed through a variety of means. . In the 2005 Residential Energy Consumption Survey (RECS), the EIA found that Appliances and Electronics accounted for 3.25 quads or 31% of household energy use in U.S. homes. In 1978, Appliances and Electronics represented (only) 1.77 quads, 17% of household energy consumption.

[7] Losses due to transmission can be measured using the formula Resistance= voltage ÷ current (Siemens, 2011). Generally speaking, energy is discharged during transmission through magnetic oscillation, a trait of alternating current (AC). This loss is greatly reduced by employing high-voltage direct current (DC) lines, as DC lacks the oscillation of AC (ABB, Inc., 2012)

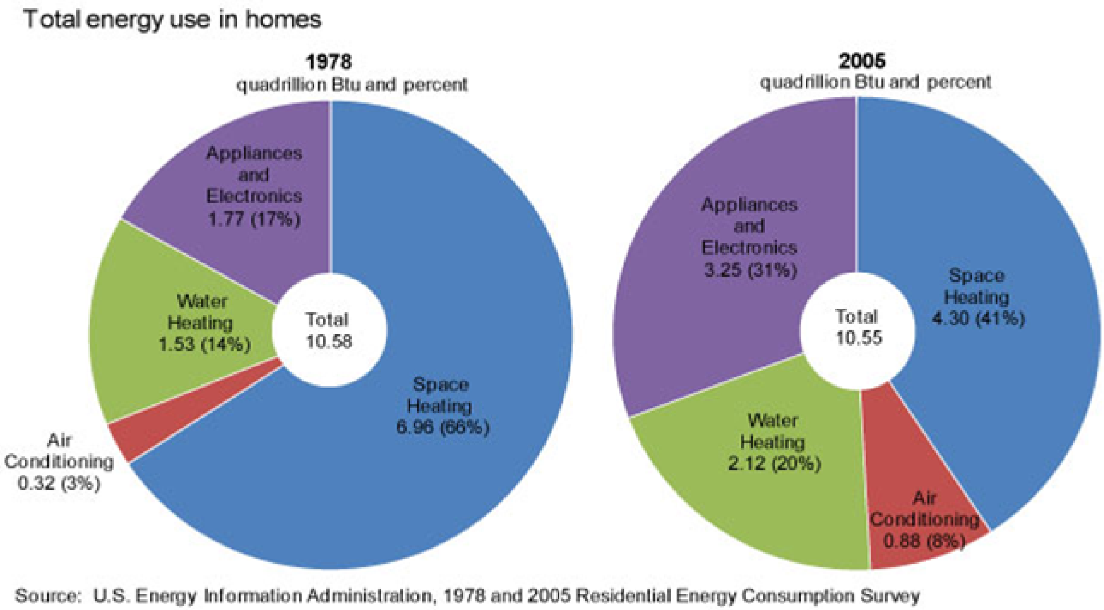

Figure 1. Total energy use residential breakdown, U.S. 2005 RECS

Clothes washers and dryers, televisions and computers, refrigerators and freezers all consume energy, however space heating, space cooling, and water heating consume the greatest amount of energy: in 2008, they comprised 72% of *domestic energy consumption* within the U.S., 12.23 quads. In comparison, the U.S. consumed a total of 99.4 quads that year, all sectors combined (EERE, 2011).[8] When considering the fuel required to produce such a vast amount of energy, it is important to recognize the portion accounted for by imports, roughly 25% or 26 quads of energy (EIA, 2009). This garners as much attention as the grand total; our national security and stability are influenced by our reliance on oil imports and our actions, as a country, are often dictated by that reliance.[9]

New sources of energy will help sustain our current level of consumption; however the pool of potential, untapped sources of energy is, at present, not large. Increased support for research and development into renewable resources such as

[8] EERE stands for Energy Efficiency and Renewable Energy, a department of the U.S. Department of Energy.
[9] This reflects the author's opinion, not an official stance by the military or any governmental body.

solar, wind, tidal, and geothermal are expressions of the country's continuing search for energy. However our national output of energy from renewable resources totaled only 7.7 quads. While this number is an improvement from prior years (just under three quads in 1975), it is rather minor when compared to the 78.4 quads of energy generated through the combustion of fossil fuels (EIA, 2011). This is a substantial increase from the 1975 figure of 29 quads.

With such heavy reliance on fossil fuels, an appraisal of resources is needed. While very difficult, an estimate is possible, using past extraction rates, the rate at which production increased in the past, the number of active wells, regions as yet un-tapped, rate of consumption, population growth coupled with growth in energy consumption, and many other factors. Arguably the most famous model that addresses the level of fossil fuels available at present and in the future is the Hubbert Curve[10].

Amidst the gloomy forecast of dependence on foreign fuel, sponsored weatherization and efficiency measures available to the nation can be found from a variety of sources. One of those sources is the American Recovery and Reinvestment Act (ARRA) and through it, the U.S. Department of Energy (DOE) dispersed $5 billion to the states for the purposes of assisting low-income homeowners with the task of weatherizing their homes (EERE, 2011). This is accomplished through a variety of means but often involves dispersing funds to local non-profit organizations that provide retrofitting to homeowners at a reduced rate. Complementing the work of these non-profits and on occasion working as partners are utility companies. By offering incentives or rebates to clients, the utilities encourage homeowners to undertake retrofit measures or upgrade old and inefficient appliances.

1.4.2 State

The portion of ARRA funding directed toward Washington State totaled $59,545,074 and was complemented by a series of grants available through the

[10] Made (public) in 1949, the "Hubbert Curve", named after Dr. M. King, predicted the peak in U.S. oil production would occur around 1970 (Ecotopia, 2011).

State Energy Program (SEP), through which grants are made available for research and development initiatives ranging from alternative fuels to renewable energy to carbon capture and sequestration (WA Department of Commerce, 2009).

Washington State, along with Oregon, Idaho, and to a lesser extent Montana, is somewhat unique among the lower 48 states, in terms of energy resources, due to the presence of the Grand Coulee dam and other dams along the Columbia and Snake rivers. These sources of hydroelectric power provide WA consumers with an average price of $0.077 per kilo-Watt hour (kWh), one of the lowest rates in the country (as compared to $0.20 per kWh in Connecticut; EIA, 2011). The unusually low price of electricity has not impeded the pursuit of energy conservation, a pursuit guided by the Northwest Power and Conservation Council (NPCC): a body of eight people, 2 per the states of Washington, Oregon, Idaho, and Montana, charged, quite simply, with “creating a power plan for the region” (NPCC, 2011). In its *Sixth Northwest Conservation and Electric Power Plan*, the NPCC states enough conservation potential exists and is (cost effective) within the Pacific Northwest to “meet 85% of the region’s load growth for the next 20 years” (NPCC, 2011).

1.4.3 U.S. Military and Joint Base Lewis-McChord

In fiscal year (FY) 2009, the Department of Defense (DoD) expended $3.6 billion on “facility energy consumption” (Office of the Deputy Under Secretary of Defense, 2011). As this report deals primarily in units of energy rather than units of currency, the following represents consumption in Btus: in 2009, the DoD consumed 880.3 trillion Btus of energy (EIA, 2011). Divided by the number of active military and civilian personnel, 2.1 million, the per capita consumption was roughly 250 MBtus (Karbuz, 2007). Progress is a continual process, however, as is evidenced by comparing historic amounts of energy consumption with current rates: the DoD consumed 1,360 trillion Btus in 1975.

In 2007, Joint Base Lewis-McChord consumed 2.7 trillion Btus, roughly two percent of the state’s total consumption (Wilson, 2007; EIA, 2011). Unless the military implements measures to increase efficiency on base, this amount of energy consumption will only increase (a result of the growing population of the base). Four directives, the Energy Policy Act (EPAct) of 2005, Executive Orders (Eos) 13423 & 13514, and the Energy Independence and Security Act (EISA) of 2007 are helping propel JBLM toward a "reduction of energy-consumption intensity by 3% annually and 30% by FY15, relative to FY03 baseline" (Comprehensive Energy and Water Master Plan: Joint Base Lewis-McChord, 2010). Potential measures to achieve the goal include the institution of an energy awareness campaign, replacing and upgrading HVAC, window, and lighting systems, and installing additional insulation.

CHAPTER 2: BUILDING SCIENCE BACKGROUND

2.1 Conduction, Convection, and Radiation

The passage and exchange of heat is called thermal transfer and it occurs in three different ways: conduction, convection, and radiation. Conduction is the passage of kinetic energy (heat) from one molecule to the next within a solid material. Convection is on a larger scale and works primarily through the passage of air. For example, warm air is discharged from a heater and as that warm air travels through ductwork, it transmits

the kinetic energy it possesses (Aubrecht, 1995). The third way heat is transferred is radiation, the broadcast of energy from one place to another.

Convection, conduction, and radiation are the three forms of thermal (energy) *transmission*. The three primary *sources* of thermal energy (heat) within a built structure are solar radiation, occupants of the building, and mechanical or electrical devices (Diamant, 1971). Solar radiation is sunlight and it finds its way inside buildings through windows and through the radiation of heat resulting from the reaction of the roofing material and sunlight. "Occupants of the building" refers to the living organisms residing within a built structure who radiate heat at all times. Mostly this refers to people, who radiate a range of energy from 145 watts, or 20.4 Btu/hr from a grown to 65 watts, or 9.2 Btu/hr from an infant (Diamant, 1971).

Appliances powered by electricity generate heat due to the imperfect, inefficient conduction and usage of electricity and the greater the inefficiency, the greater the heat (Diamant, 1971). For example, in an internal combustion engine petrol is fed to an engine, which is combusted in the engine block, driving pistons which turn the crankshaft to produce motion. Heat is radiated at every step of the cycle, and represents a loss of energy; only 25% of the energy contained in the petrol is converted into motion, and even less for *forward* motion, as low as 14% (U.S. DOE, 2011).[11]

When establishing the efficiency for a furnace, one looks for the Annual Fuel Utilization Efficiency (AFUE), a ranking describing how much of the energy entering the furnace is converted in to heat, versus up a chimney, for example. Thus an AFUE of 92.5 indicates 92.5% of the energy within the fuel used by a given furnace heats the dwelling, while the other 7.5% escapes in different ways, through different inefficiencies, for different fuels. Standard hot water heaters, those with a large tank containing 30-60 gallons of water and using either electricity or natural gas to heat the water, lose energy in several ways. One is through maintaining a reservoir of heated water, regardless of use. Another is heat loss to the ground beneath the unit (conduction) and to the ambient air (convection), both of which can be greatly reduced through the use of insulation.

Light bulbs emit energy in two forms, light and heat, and in many instances the energy radiated as heat is greater than the energy radiated as light. For example, an incandescent light bulb produces light by moving enough electricity through a thin wire (the filament, usually made of tungsten) to make the wire "white-hot". Thus light bulbs perform two functions, one illuminating a space and the other, heating a space. This impact is an important consideration for modeling energy consumption within a house, as replacing incandescent light

[11] The sum of energy loss can be divided into: 70-72% in the engine (radiator, exhaust heat, etc.); 17-21% power to wheels (rolling resistance, braking, etc.); 5-6% parasitic losses (water pump, alternator, etc.); and 5-6% drivetrain.

bulbs with compact florescent lights (CFLs) will reduce the energy load for lighting, but will increase the load for heating (at least during cold weather).

In considering the efficiencies of electric appliances and natural gas-fed appliances, it behooves one to be familiar with the efficiency losses of both electricity and natural gas as fuels consumed by the residential sector. Electric appliances operate at very high efficiencies because there is little loss of energy in heating a cooking element or furnace, for example; utilizing the energy potential of natural gas requires a change of state and an imperfect capture of energy released during the transformation leads to a comparatively less efficient appliance. This is a superficial assessment, however, because the inefficiency in generating electricity, primarily due to friction, resistance of the conducting material, and heat loss, is far greater than in combusting natural gas for energy consumption.

2.2 R-value & U-value

In order to guard against the unwanted transmission of heat (from indoor to outdoor and vice-versa), houses are lined with insulation, in the walls, ceiling, and sometimes within the roof. Insulating materials are poor conductors of energy, and slow the loss of heat through conduction. Two systems of measure are in place to rate the effectiveness of insulating materials: walls, roofs, and other structural spaces are given an *R-value*, the material's *resistance to heat transfer*. Windows, skylights, and other installations featuring transparent or translucent material receive a U-value, a representation of "the number of Btu[s] that flow through one square foot of material in one hour" (Darling, 2011). The two values describes the same quality, a material's ability to transfer heat, but while a high R-value indicates a high resistivity to thermal exchange, a low U-value indicates (only) a small amount of energy passes through the material in question. In other words they are different expressions of the same characteristic and are described by the metric Btu/hr-sq ft °F in the U.S. or W/m^2 °C (Darling, 2011). [12]

[12] A "British thermal unit" (Btu) is a measure of the heat content of fuels. It is the quantity of heat required to raise the temperature of 1 pound of liquid water by 1°F at the temperature that

2.3 Envelope, Insulation, & Ducting

R-values and U-values provide performance ratings for insulating materials, yet the term *insulation* usually refers to one of two "distinct processes at work" (Reid, 1999). Resistance insulation refers to that material slowing the thermal transfer. This may refer to clothing preventing or slowing the passage of heat from the body outward, or to materials within a built structure that prevent heat loss in the cool months and heat gain in the warm months. Capacity insulation refers to absorption capacity of the air within an enclosure. The larger the volume the more time is necessary to affect temperatures. Or, the longer the lag time between applying energy to an existing volume and feeling the effects. For example, a very large house possesses high capacity insulation because a large quantity of energy is required to affect all the air residing the envelope. A small house has low capacity insulation because a relatively small amount of energy is required to affect the small amount of air in the envelope.

The building envelope (envelope) prevents direct exposure to the raw elements and it consists of the building's foundation, walls, roof, windows, and doors (U.S. DOE, 2010). A tight envelope secures the house against the exchange of conditioned air, while a leaky envelope allows the exchange of conditioned air for external, unconditioned air. When this exchange takes place, the conditioning appliances (furnace, A/C unit, heat pump, etc.) must work constantly to heat/cool the newly introduced air.[13]

2.4 Joint Base Lewis-McChord

Understanding how heat is transferred within a house and the metrics used to gauge efficiency provides an addition way to measure the level of success in retrofitting measures: how effective those measures are in preventing the

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water has its greatest density (approximately 39°F). One Btu is approximately equal to the energy released in the burning of a wood match (U.S. EIA).

[13] According to the U.S. DOE, the residential sector within the U.S. consumed roughly 1316.729 trillion Btu's from February 1st through the 26th, 2010.

undesired loss of heat, of conditioned air to the exterior environment from the interior. The exterior environment is Joint Base Lewis-McChord (JBLM) and the houses studied reside on the residential section of JBLM, located West of the Cascade Mountains in Washington State, roughly half way between the cities of Tacoma and Olympia.

"BRAC" is an acronym that stands for Base Realignment and Closure and is the process employed by the Department of Defense (DOD) to ensure the integrity of base closure and reorganization (DOD, 2011). BRAC results in closures, expansions, and mergers throughout all branches of the armed forces. The 2005 round of BRAC saw the merger of Fort Lewis and McChord Air force Base and the resulting formation of JBLM. JBLM occupies 90,880 acres in Thurston and Pierce counties and houses approximately 16,300 people, including soldiers on active duty and their families (JBLM media relations, personal communication, April 11, 2011). [14] This number is expected to rise in the future due to the BRAC process. As a corollary figure, approximately 47,160 people work on base by participating in the daily operations and affairs of JBLM, but do not necessarily live on base. This number is a dramatic increase from 27,888 in 2003 and a slightly smaller count than the expected population of 2016, 48,389 (Comprehensive Energy and Water Master Plan: Joint Base Lewis-McChord, 2010).

In many respects, JBLM resembles a large town or community in population and in the many services offered, and is in fact the sixth largest city in Washington (personal communication with Eric Waeling). If hungry, one will find Manchu Wok, Charley's Steakery, Cinnabon, Koibito Sushi, and Robin Hood Sandwich Shop at the Exchange (similar in function and intent to a mall) and several more located throughout the base grounds (U.S. Army, 2011). For entertainment, one finds a movie theater, an arts-and-crafts center, golf center, a paintball field, and a collection of retail stores including Sprint, Gamestop, GNC

[14] The Yakima Training facility was incorporated into the Joint Base Lewis-McChord merger, but as this study focuses on REE and the Yakima training facility has no full time residents, all statistics and values refer to the (primary) base located in Western Washington.

Supplement center, as well as various salons and cafés (The Exchange, 2011). Tacoma Power Utilities provides the base with electricity and Puget Sound Energy supplies the base with natural gas. It is one of the largest military complexes on the West Coast and operates simultaneously under six different sustainability mandates (personal communication with department of media relations, JBLM, 2011)[15].

2.4.1 Fort Lewis

On January 6th, 1917, residents of Pierce County voted on a $2 million bond to purchase roughly 62,432 acres of land on the Nisqually plains and invited the US army to build a base, provided the army construct and occupy the base permanently. The army accepted the invitation and on July 5th 1917, construction began on Fort Lewis, named after Captain Meriwether Lewis of the 1804 Lewis and Clark expedition. The first recruits to be trained at Fort Lewis arrived in early September, 1917 and by December 31st, "37,000 officers, cadre, garrison, and trainees were on post" (Fort Lewis Museum, 2011). The fort served as a training facility during World War I and served the 91st Infantry Division as well as the 13th Infantry Division, which did not actually deploy due to the signing of the armistice November 11th, 1918 (United States Army).

The peace-time following the conclusion of WWI led to a sharp reduction in military funding and a consequent lull in Fort Lewis operations. In May of 1926, congress approved $4.5 million to rehabilitate three bases across the country, of which Fort Lewis was one. With $800,000 in hand, the army began constructing permanent structures (brick vs. temporary wood-built structures) and securing the future of the fort.

2.4.2 McChord Air Force Base

[15] EO 13514 (2009) Federal leadership in Environmental, Energy and Economic Performance; DoD SSPP (2010) The DoD Strategic Sustainability Performance Plan; Army Strategy for the Environment; ASCP (2010) The Army Sustainability Campaign Plan; Installation Management Campaign Plan (2010-2017); Installation Sustainability Program (2002). ~Paul Steucke, Environmental Division-Public works, JBLM, WA

On April 21st, 1929, construction began on Tacoma field, a 1,000 acre airport hosting a 3,000 foot landing circle, a 5,400 foot runway, and a hangar boasting 27,600 square feet of storage space among other things (McChord Air Museum). On May 5th, 1938, Peirce County passed the title for the airport to the War Department amidst struggling finances. Shortly thereafter, the military christened the field McChord Field, honoring Colonel William C. McChord of Richmond, Virginia. By 1939, the field would boast 5 hangars, 3 runways, housing (including a 1,285-man barrack), a radio transmitter building, hospital, central heating plant, electric distribution system, and a 300,000 gallon water tower among other features (McChord Air Museum).

2.5 Elements of Energy Efficiency on Joint Base Lewis McChord

Residents of JBLM do not pay for electricity or gas, with the exception of usage roughly 30% above the mean for a given housing community (McMakin, 1999; U.S. Department of Defense, 2005; U.S. Department of Defense, 2008). The mean usage is calculated on a monthly basis. For example, if the communal average electricity usage is 850 kWh in a given month, and a household uses 1150 kWh in that month, that household is charged for the amount of energy consumed above the communal. The absence of a usage-based fee reduces the occupant's financial motivation to conserve energy and when making comparisons to other non-military compound studies, this impact must be considered.

A second impact on energy usage is the duration of occupancy on base and homeownership: occupancy ranges from six months to approximately three years and no one owns their house. Conventional wisdom holds the greater the duration of study or observation, the greater the accuracy of estimations resulting from that study or observation due to a greater population base. Another result of absent homeownership is lack of incentive to invest in weatherization and other energy-saving retrofits. Home ownership provides incentive to invest in energy efficiency measures because a) the value of the house increases, once retrofitted, and b) the costs associated with basic utilities decreases.

A third impact is the independence of the residential sector from the other base operations. The 2010 Comprehensive Energy and Water Master Plan for Joint Base Lewis-McChord lays out current consumption of both water and energy on base, includes recommendations for improvements, as well as a plan to implement the recommendations. The exception to the plan is the residential (termed *family housing* in the report) portion of the base. The residential structures within the base are managed and maintained by Equity Residential while the utility billing is managed by Minol USA.

This impact is felt through structural and financial avenues: because buildings outside the residential area are managed directly by the military, directives aimed at reducing energy consumption will be funded & carried out to specified buildings by the military. While the private entity managing the residential portions of the base receives payment for its services from the military and commands a respectable pool of resources, it is nonetheless quite small in comparison to the military's.

2.6 Management of Property and Billing on Joint Base Lewis-McChord

2.6.1 Equity Residential and Housing Stock

Equity Residential (EQR) manages the residential real estate on JBLM. It is a property manager, owning or investing in 442 properties consisting of 127,711 apartment units in 17 states and the District of Columbia (EQR, 2010). In April of 2002, 2 firms from the private sector, EQR and Lincoln Property, began managing the residential properties on Ft. Lewis and McChord AFB, making Ft. Lewis the second military base to divest residential property management to the private sector. While Lincoln Property coordinated new construction in Ft. Lewis, EQR oversaw the remaining obligations and responsibilities on Ft. Lewis as well as new construction in McChord AFB (M. Greer, personal communication, December 1st, 2011). The remaining obligations and responsibilities include renovation, retrofitting, and maintenance of existing houses. As the entity responsible for the physical state of housing on base, EQR was closely involved with nearly all elements of the study and acted as a resource of building data and records of prior work or work-plans, the workforce responsible for correcting any problems that may arise with the house, and is a likely candidate for implementing retrofit designs arising in the future.

Within the Fort Lewis portion of JBLM there are 15 residential communities consisting of more than 1,800 buildings and over 3,700 units. This study evaluated six of those communities: Broadmoor, New Hillside, Beachwood, Davis Hill, Evergreen, and Discovery Village/Miller Hill (DV/MH). While the houses within these communities were constructed over a period of nearly 80 years, the overwhelming majority was constructed in the late 1960s-early 1970's and possesses certain similarities in design, manner or style of construction, and in the material used in construction. These similarities include spacing of framing studs, architectural layout, style of windows, type of furnace & hot water heater[16], and the manner in which conditioned air & water are distributed throughout the house.

The communities with ductwork (all but the historic Broadmoor homes) have trunk lines with neither insulation nor sealed seams and branch lines insulated to R-8. All houses have programmable thermostats, three exterior entrances, and the vast majority is situated on slab-on-grade foundations. In 2003, EQR began a three year program focused on replacing all existing furnaces to high efficiency (92%) sealed-combustion gas furnaces.

Broadmoor is predominantly composed of single family residences built in 1931 or prior. The historic buildings are anomalous, relative to the newer buildings, because they are under historic preservation and there are restrictions on the type of renovation and retrofitting based on the degree of physical (structural) invasiveness. This results in buildings with large footprints, ranging in size from 1,865 ft^2 to 2,650 ft^2, minimal insulation, single-pane windows, little weatherization, and antiquated hydronic heating systems. In addition, the historic houses in the Broadmoor community have unique features such as two stories, basements, additions to the original structure, and fireplaces.

[16] "Type" refers to fuel source, efficiency rating, sizing requirements, etc.

The remaining housing stock within Broadmoor is composed of multi-unit structures built in 1934, 1939, and 1948, and single family dwellings built between1959-1963. The multi-family buildings are excluded from this study largely due to aggregate gas metering per building. The newer single-family dwellings are included in the study and have characteristics such as crawl spaces covered in cement (also known as a “rat-slab”) with ductwork routed through the crawlspace, large glazing surfaces, and fire-places.

Beachwood, New Hillside, and Davis Hill share many characteristics as a result of vintage and of retrofit measures: they have slab-on-grade foundations, are of early 1960’s vintage, and range in footprints from 1154 ft^2 - 1262 ft^2. Light fixtures are primarily CFL, windows are double-pane with vinyl frames, and most units feature three bedrooms. 95% of ductwork is located in the ceiling. The hot water heater and furnace are housed within a mechanical room, located within the structure and accessed from either inside or outside, depending on the particular unit. Units with mechanical rooms accessed from outside include louvered doors and are locked to the occupants, accessible only by EQR technicians.[17] The communities are composed mostly of duplexes; units have common rooftops above carport space, not common walls.[18]

Beachwood differs slightly from the Davis Hill and New Hillside. A portion of the community is composed of newer dwellings constructed in 2003-2005 which are composed of duplexes ranging in size from 1497 ft^2 - 2263 ft^2. However, these were not included in the study due to the relative lack of necessity concerning retrofitting. Those units included in the study featured footprints up to 1580 ft^2 and nearly half are single-family residences.

Evergreen also experienced two stages of development, the first in 1984 and the second in 1995. The earlier vintage homes have slab-on-grade foundations, range in size from 1200 ft^2 - 1560 ft^2, have predominantly incandescent lighting, double-pane aluminum, first generation windows, and have

[17] Units with mechanical rooms accessed from the inside are also accessible only to EQR technicians.

[18] There *is* a wall dividing the carport space between the two units however its function is solely to divide one exterior space into two; the carport remains a carport.

two to three bedrooms. The houses built in 1995 range from 1600 ft^2 - 1900 ft^2, have two to three bedrooms, and are far fewer in number.

The newest of the communities is Discovery Village and its subset, Miller Hills. Constructed between 2005 and 2007, these homes feature modular construction, energy efficient envelope design and construction materials as well as Energy Star appliances. The footprints range between 1,711 ft^2 and 1843 ft^2, and have three to four bedrooms. An important distinction between the units in DV and MH is the installation of tankless water heaters in Miller Hill. The opportunity to gauge the relative efficiencies between water heaters accounts for their inclusion in this study.

2.6.2 Minol

Minol is a German-based company specializing in energy management including water and energy conservation, comprehensive utility billing, sub-metering, and metering research and development (Minol, 2011). Minol USA is a satellite entity, managing operations in the U.S. (as the name suggests) including the billing operations for electricity and natural gas on JBLM. Beginning in September 2005, Minol USA began assisting the military in transitioning from a free consumption system, where residents paid no money regardless of lifestyle[19], to the present system of minor incentive/disincentive. This function is one Minol USA has performed for the military in the past and will, presumably, continue to do so in the future. Residents are notified of the upcoming change to the established no-fee system, and a year-long mock-billing cycle is put in place to facilitate the transition.

[19] A descriptive anecdote: (some) residents would turn the heat as high as it would go, then open the windows to moderate the overall interior temperature.

CHAPTER 3: HISTORICAL BACKGROUND AND LITERATURE REVIEW

3.1 Building Materials and Insulation

The field of residential energy efficiency (REE) is multi-disciplined, drawing from the fields of architecture, chemistry, and physics, among others. In order to establish a historical perspective on REE, I will draw on the history of architecture to illustrate practices recognizable for their contributions to REE's evolution. Within this history lie improvements to the building envelope, including structural advancements and the incorporation of and improvements to insulation, and the design of heating and cooling systems.

For the purposes of this project, the review of residential energy efficiency begins in the 17^{th} century, in the colonial/post-colonial period of American architecture. Construction practices in the 17^{th} century relied on well-established building materials, such as wood, brick and mortar, and on occasion stone and cob. Handlin (1985) describes common residential building practices in early 17^{th} century Virginia as consisting of wood and using brick primarily for foundations and chimney; neither material possesses high or even moderate insulation values. Other accounts, such as Kimball & Edgell (1918) suggest the composition of Virginian housing (at that time) to contain a high percentage of clay-based structures, with a push toward brick housing. However the "first house wholly of brick does not seem to have been built until 1638" (Kimball & Edgell, 1918). Methods and designs involved the use of standard tools (hammer & nails, saw, chisel, spade, etc.) and included log cabins, post-hole construction, Mortise and Tenon joining (as depicted in figure 1), and small one to three room houses.

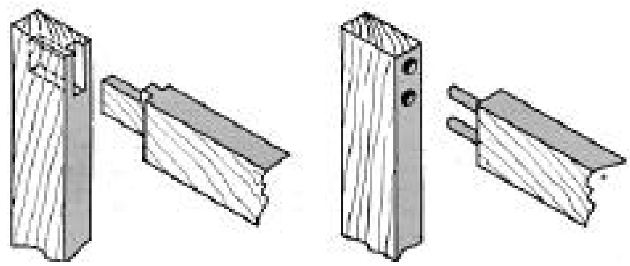

Figure 2. Mortise and Tenon joining.

Handlin and Kostof (1985) note an increase in Victorian-style, multiple storied mansions toward the end of the 17th century. While possessing different physical capacities for strength (density, brittleness, flexibility, load-bearing capacity, etc.), the basic building materials lacked the inherent insulating capacity to isolate the interior (building) environment from outside temperature fluctuations.[20]

The next significant jump in housing, with respect to REE, did not occur until the early 19th century, when a particular style of construction began to emerge: the *balloon-frame* model. This style is significant because of a) its pervasiveness, assisting in the facilitation of expansive westward movement, and b) its representation of "protoindustrial building practices" (Cavanagh, 1997).[21] Houses built in the balloon-frame style are designed to have each component wall assembled on the ground, then raised and secured to one another. Because this style of construction requires a relatively modest amount of skill, houses built in this style could be erected in short period of time. However, the balloon-frame style allowed for a high rate of envelope penetration (quality workmanship sacrificed for expediency and cost) and a high potential for house fire.[22] The

[20] See Appendix B for R/U-values of building materials.

[21] Cavanagh expands thusly: "…it was a particular example of the "progressive" modification of conventional building practices. These progressive practices would reduce craft labor, produce components industrially, revise the method of assembly, simplify the joint or develop an identifiable connector, employ lightweight materials, and improve structural efficiency". (Cavanagh, 1997).

[22] The issues with insulation and fire both involve a particular element in the design of the balloon house, the wall cavity. The term "wall cavity" refers to the gap between the studs, extending from the sill to the eaves with no barrier separating the first and second stories. This created a chute for fire to quickly travel between stories.

balloon frame method of residential construction is a foundation for modern building practices and lead to the platform style of construction and further compartmentalization of framing (McAlester,1994).[23] One characteristic of this style important to this history of REE is the wall cavity: the space between studs is an ideal location for insulation.

While the structural features of housing slowly evolved, so too did insulation. However, documenting the contribution of insulation to REE presents a slight challenge. This is not necessarily from lack of records; Ancient Egyptians employed asbestos in the embalming process and ancient Persia imported a similar process from (ancient) India, while ancient Greece incorporated asbestos into clothing, enjoying the mineral's numerous insulating and protective qualities (Ringsurf, 2009). Within building science and the history thereof, it can be difficult to separate motivations for building in a particular fashion or using specific materials. Function over form? Did a builder choose a particular material for building because of its structural strengths, resistance to rot, insulation capacity, or none of the above?

Many contributions to the evolution of the (residential) built structure and to insulation arise from the culture brought to the U.S. with the arrival of immigrants from other countries. For example, Ostrander & Satko (2011) note that plans dating to 1805 credit the English with a cavity-wall style of masonry, where in a 6-inch gap separating an interior and exterior brick wall provided protection from moisture and if well-constructed, such a double-wall would serve as excellent insulation.

Gaynor (1976) describes a contribution found among German immigrants in the town of Zoar, Ohio, called the "Dutch Biscuit", a construct composed of wood planks wrapped with mud, hay, and sometimes lime. When placed between two levels (attic-ceiling or floor-basement), the Dutch Biscuit provided a

[23] Platform building modified the balloon-frame method by essentially dividing the building structure into two individual units, one built directly atop the other. The result is a two story house, the same as a balloon-frame yet the additional steps introduced a barrier to fire and further structural support (Calloway, 1991)

moderate degree of protection against thermal conduction and potentially convection as well, depending on the individual instance.

Wyllie-Echeverria & Cox (1999) and Dowling (2009) wrote on *Zostera Marina*, or Eel grass, a marine plant employed by generations by Nova Scotian and New Englanders for its insulation capability, compressibility, durability, and resistance to fire. In 1891 Samuel Cabot, Inc. developed "Cabot's Insulating and Deafening Quilt", or "Cabot's Quilt…by stitching various thicknesses of dry *Z. marina*, leaves between layers of heavy Kraft paper" (Wyllie-Echeverria, S., Cox, P., 1999).

While the Dutch-Biscuit and eel grass served as insulators within specific geographic areas, they did not find wide-spread acceptance as insulators. Mineral wool is one of the first materials produced on a commercial scale and used as insulation in industrial, commercial, and housing applications. Numerous academic ventures into the origin of mineral wool have delivered numerous different claims of ownership: Warnford-Lock (1889), Thornbury (1938), Singh & Coffman (1991), and Panayi (2007) attribute the manufacture of mineral wool to different people in different times and different places, ranging from England, to Russia, to Germany. Bynum (2001) states the earliest recorded commercial production of mineral wool (used to insulate pipe) is in Wales, during the year 1840. Lamm (2007) writes that mineral wool's close cousin, glass wool, possesses an equally diverse history: originally patented in Paris, France, the capability to produce glass wool on an industrial scale was developed in the U.S.by Owens-Illinois in 1931.[24] Bynum provides addition background, dating usage of glass fibers to ancient Egypt.

Rigid insulation is synonymous today with foam-board insulation and is commonly referred to as Styrofoam (extruded polystyrene), yet modern foam-board insulation incorporates several different types of manufacture for different purposes. The U.S. Department of Energy provides a listing of the types of rigid

[24] Owens-Illinois was a company originally known for producing fiberglass; the term *fiberglass* refers to a resinous compound of composed plastic and glass fibers; when molten, the compound is poured into a mold, forming panels in the shape of the mold. *Fiberglass insulation* resembles cotton candy, though instead of spun sugar, the fluffy matrix is composed of spun glass.

foam board insulation, including molded expanded polystyrene, extruded expanded polystyrene, polyisocyanurate, and polyurethane (U.S. DOE, 2011). Rigid board insulation is not new; Bock (1992) identifies several types of rigid board insulation composed of compressed cellulosic material (organic, woody byproducts); among them are Insulite, Cane Board, Inso Board, Maftex, Flax-linum, and Balsam Wool. These products first appeared around 1912, but were more aggressively marketed during the 1920's.

3.2 Standardization of Building Requirements

While history provides the opportunity to ascertain who developed what, when, and where, it also identifies organizations responsible for developing or furthering research on a subject. An example of this can be found in the development of the guarded hotbox, an apparatus used to test and rate insulating material such as mineral wool, rigid insulation, glass-wool insulation, and even saw dust for thermal conductivity (Southern Ice Exchange,1897; Butterfield, 1916).

In the instance of the guarded hotbox, the American Society of Refrigerating Engineers (ASRE) submitted a request to Congress for, in essence, usable data with which to design refrigeration products (NIST, 1999). Congress responded with funding to the newly-formed National Bureau of Standards (NBS) and research into the guarded hotbox ensued. Societies such as ASRE and NBS, now the National Institute of Standards and Technology, articulate the need for technological progress, and (often) provide funding in addition to communication with individuals and bodies in possession of needed resources. In *Proclaiming the Truth: an illustrated history of the American Society of Heating, Refrigerating and Air-conditioning Engineers, Inc.*, Comstock and Spanos recount the merging of ASRE with the American Society of Heating and Ventilating Engineers (ASHVE).[25] Their work provides a measure against which modern standards can be compared against as well as a fascinating context in which one can place the

[25] In 1954, ASHVE changed its name to the American Society of Heating and Air-Conditioning Engineers (ASHAE), reflecting the rise in forced-air (conditioning) systems in buildings (Comstock and Spanos 1995).

progress of (the) industry. For example, Stewart A. Jellet recounts how “Until about 1890 the business of heating and ventilating had been largely based on the most ancient rule known to engineers, the rule of thumb…” (Comstock, 1995).

While windows into our cultural and technical history intrigue and fascinate, the year 1975 saw ASHRAE’s development of Standard 90-75 (Energy Conservation in New Building Design), and Standard 62-73 (Standards for Natural and Mechanical Ventilation). [26] While the standards resulted from many laborious hours by ASHRAE, they represented the culmination of efforts by many organizations. In the case of Standard 90-75, ASHRAE worked off a 1974 NBS energy conservation report (NBSIR 74-452) at the behest of the National Conference of States on Building Codes and Standards (NCSBCS) to develop a national building standard incorporating energy efficiency (Jarnagin, 2010). These two standards interacted with existing building codes, forcefully encouraging the employment and utilization of more energy efficient building styles and methods in place of more traditional methods, methods (often) borne from the rule of thumb.

Primary impacts of Federal Standard 62-73 included the standardization of requirements for indoor air quality (IAQ) and the changes to building methods and materials necessitated by (the implementation of) Standard 62-73. In order to accommodate the needed number of air changes per hour, a given building needs to have a ventilation system or central air system capable of delivering clean air to the proper location. These required, by law, changes to the design and installation of windows and doors, vents, ventilation conduits, and any element of a building with an impact on air movement. As time progressed, revisions to the standard occurred to accommodate improvements in technology as well greater understanding of building science and its interaction with the health and comfort of a building’s occupants. In *Building Standards and Codes for Energy* Conservation, Gross and Pielert (1977) describe the evolution of ASHRAE Standard 90-75 (90-75), from several pieces of federal legislation to its delivery in

[26] In 1916, “Margaret Ingels becomes the first woman in the world to earn a degree in mechanical engineering”- *The ASHRAE Centennial:* 100 Years of Progress

October of 1975, one of the first energy efficiency standards applied to the building industry.

One evaluation of the standard, performed by Arthur D. Little, Inc., assessed the implications of 90-75 and found it would reduce "annual energy consumption in all building types and locations" (Little, p 20). Specifically, Little, Inc. found 90-75 stood to increase the energy efficiency in buildings of the 1970-era by: 11.3% in single family residences; 42.7% in low-rise apartment buildings; 59.7% in office buildings; 40.1% in retail stores; and 48.1% in school buildings (Education Development Center, Inc., 2011).

From 90-75 arose Public Law 94-163 in December 22nd, 1975 & Public Law 94-385 in August 14th, 1976. Public Law 94-163 offered financial assistances to those states desiring or considering implementation of energy codes (Gross and Pielert, 1977). Public Law 94-385 includes within it: *Title III, Energy Conservation Standards for New Buildings Act of 1976*, a measure requiring the development of a national standard for energy efficiency and requiring states to meet that national standard (Gross and Pielert, 1977).

3.3 The Oil Embargo of 1973 & NPCC/WPPSS

The catalyst for the standard 90-75 was necessity. The necessity, or perceived necessity, arrived in the form of the 1973 oil embargo. The Organization of Arab Petroleum Exporting Countries (OAPEC) ceased exporting petroleum to the U.S. and Holland for their support of Israel in the Yom Kippur war. The U.S. responded by forming the national Strategic Oil Reserve, President Nixon signed into law the Emergency Petroleum Allocation Act, and energy efficiency rose to the forefront of national attention. [27] Gasoline shortages and rationing highlighted automotive fuel economy and the inadequate thermal

[27] President Ford would later enact the Solar Energy Research Development and Demonstration Act of 1974, create the Federal Energy Administration, and the Carter Administration would pass the Public Utilities Regulatory Policy Act (PURPA) in 1978, establish the Department of Energy, a National Energy Policy, and would erect solar panels on the roof of the White House. The Reagan administration removed the solar panels.

performance (illustrated through utility bills) of buildings received critical notice, prompting efforts to increase the thermal performance of buildings.

While the country struggled to reduce usage of and dependency on oil, Washington State experienced a different energy-related struggle called the Washington Public Power Supply System, or WPPSS (or "Whoops"). The Northwest Power and Conservation Council (NPCC) provides a succinct and remarkable recounting of WPPSS, describing it as a program designed to meet the expected linear and unflagging rise in both energy consumption and population through the construction of new power generating facilities: "21,400 megawatts of thermal power — two coal-fired plants and 20 nuclear plants — and 20,000 megawatts of new hydropower between 1971 and 1990, at an estimated cost of $15 billion" (Northwest Power and Conservation Council, 2011).

Released in January of 1976, a study called *Energy 1990* predicted both a reduction in the rate of increase in power consumption and established efficiency as a legitimate means of meeting the power requirements on the part of rate-payers.[28] A second study, commissioned by the Bonneville Power Administration (BPA) and conducted by Skidmore, Owings & Merrill, revealed a substantial potential for energy efficiency existed and the development of said efficiency "would be as much as six times less expensive than building an equivalent amount of nuclear power" (Northwest Power and Conservation Council, 2011).

In the Pacific Northwest, WPPSS is largely responsible for focusing attention on energy conservation and directly responsible for the Pacific Northwest Electric Power and Conservation Act, legislation enacted on December 5th, 1980 engendering the creation of the NPCC.

The Pacific Northwest Electric Power and Conservation Act not only established the NPCC[29], but it also charged the council with the task of producing an evaluation of the Pacific Northwest's energy resources and recommendations for meeting the energy demand placed on those resources while protecting the fish

[28] *Energy 1990* was part of the negotiated settlement between the City of Seattle and pro environmental groups, who challenged the City of Seattle's involvement of in WPPSS (Northwest Power and Conservation Council, 2011)

[29] Technically, it established the NPCC's forerunner, the Pacific Northwest Electric Power and Conservation Planning Council.

and wildlife within the region (Northwest Power Act, 1980). In April 1983, the first such report, the Northwest Conservation and Electric Power Plan, delivered “a regional conservation and electric power plan and a program to protect, mitigate and enhance fish and wildlife” (Northwest Power Act, 1980). The NPCC released its sixth power plan in February of 2010.

In 1974, the City of Seattle introduced a building insulation standard into code, and in 1976, the resolutions 25257 & 25259 stated energy efficiency would be pursued as a primary method of meeting energy demand, rather than building more power plants. The state energy code arose from Model Conservation Standards, developed in the Pacific Northwest under the Northwest Power Planning Act, passed by Congress in 1980. The State Energy Code required conservation as the preferred method to accommodate load growth in the Bonneville Power Administration Region. Subsequent updated editions of the code were released in 1984, 2001, and 2009, and with each edition the basic standard for insulation, building envelope tightness and other elements of energy efficiency grew (Lynn Benningfield, John Hogan, 2003).

3.4 Studies on Residential Energy Efficiency

Washington State University Energy Extension Program (WSU EE) conducted research comparing actual energy consumption versus predicted energy consumption of Northwest Energy Star rated modular (manufactured) homes within the Discovery Village community on JBLM in the study *Measured vs. Predicted Analysis of Energy Star Modular Permanent Military Housing: Fort Lewis Case Study* (Lubliner, Kunkle, Gordon, and Blasnik, 2010). The study complements the current investigation in many methodological respects from utility billing analysis to the comparison of actual energy usage compared to modeled usage. However the current study focuses on retrofitting existing homes while the earlier study focused on new construction. In addition, the prior study uses one energy modeling program, Energy Gauge U.S. 2.8, while the current study uses two programs, SIMPLE and BEopt.

McMakin et al. authored a study in 1999, *Energy Efficiency Campaign for Residential Housing at the Fort Lewis Army Installation*, addressing energy consumption within the realm of occupant behavior. In this study, McMakin notes there is no one influence or factor determining the behavior of (housing) occupants. Thus, there is no one answer, no singular action available to successfully address egregious energy consumption. Such a statement provides relief; rather than trying to address one big problem with one big solution, numerous smaller problems can be met with multiple *manageable* solutions. The smaller the area, the greater the degree to which a solution can be contoured to individual needs, and the greater the likelihood of success. In addition, McMakin et al. provide the basis for a question: if the baseline energy efficiency of the residential buildings is increased, will the behavioral elements impacting energy usage have a reduced impact?[30]

A seminal study in the area of residential energy efficiency is the *Houston Home Energy Efficiency Study* by Hassel, Blasnik, and Hannas (2009). In it, the authors analyzed and compared the energy performance of 226,873 new houses in the Houston, TX region. Of the 226,873 homes analyzed, 114,035 were built to local code and functioned as a baseline, 106,197 were rated to Energy Star standards, and 6,641 were rated to Guaranteed Performance Homes[31]. The study found all houses demonstrated a substantial increase in energy efficiency, relative to houses built prior to 2001[32], and the baseline homes in particular performed better than anticipated, thereby lowering the performance gap between houses built to Energy Star specifications and those built to code (only). The increase in performance is due to a variety of factors, mostly within the realm of economics and the implementation of the TX energy code (Hassel, Blasnik, and Hannas, 2009).

[30] While this is an important question, it is not pursued further in this study.

[31] Guaranteed Performance Homes is a standard slightly more stringent than ENERGY STAR and upheld by a collection of organizations such as Masco, who participated in the study, Tuscon Electric Power, Advanced Energy, and General Electric.

[32] In June, 2001 the Texas legislature approved the first-ever energy code, Senate Bill 5.

3.5 Review of Existing Modeling Programs

The U.S. DOE's Energy Efficiency & Renewable Energy (EERE) department lists 393 software programs designed to produce energy consumption projections (EERE, 2011). This list is not exhaustive, yet serves to illustrate the dizzying diversity within the field of energy modeling software. The field of energy (consumption) modeling as practiced today is relatively new, yet the foundational principles are old. A settler in the early 19th century who gauges the amount of wood needed to counter a cold winter attempts to predict how much energy, released in the combustion of fuel, will be necessary to offset the migration of heat from inside to outside. Articles in trade journals dating back to 1906 document the efforts made to quantify the impact of weather upon heating and cooling load estimations: "for any given outside temperature there is a corresponding amount of heat that must be supplied in order to offset the heat losses through the walls and windows" (Fels, 1986).[33]

A noteworthy step toward the process of modeling energy consumption began within the HVAC industry, where engineers employed thermodynamics, seeking to predict heating and cooling load requirements. The development of the guarded hot-box, as described in section 3.2, represents one of the more notable contributions toward measuring an object's thermal conductivity.

[33] "Highest Economy in furnace heating: Proper temperatures, ventilation and coal consumption for different outside temperatures, *The Metal Worker, Plumber and Steam Fitter, 66* (November, 1906) 47-49. "

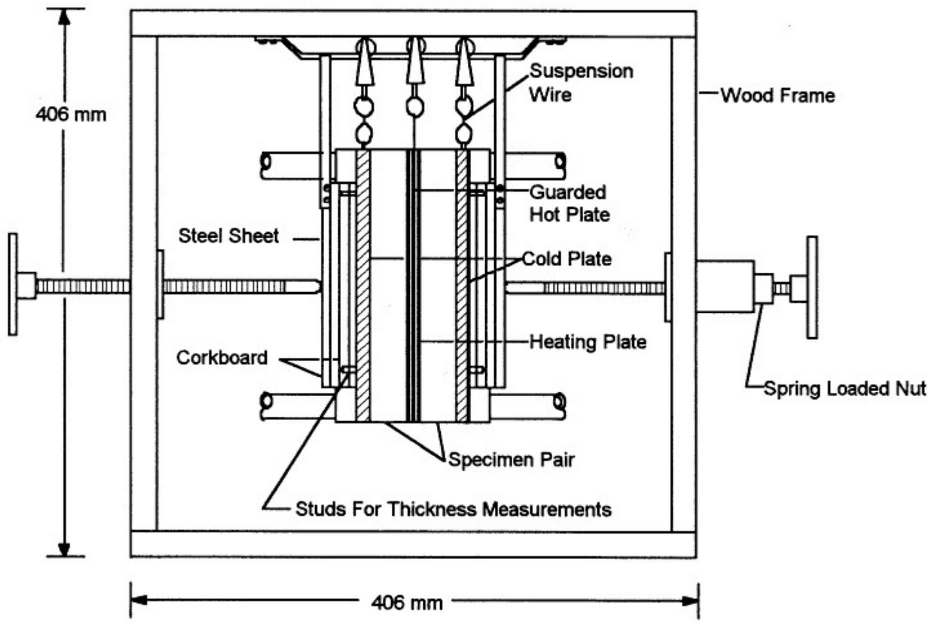

Figure 3. Schematic of NBS 200 mm guarded-hot-plate apparatus, 1928 version. (Zarr, R. 2001)

The hot-box is a construct designed to measure the conductivity of a wall assembly, accomplished by placing the test wall within an apparatus that simulates an environment where in one side of a wall is exposed to heat via an electrically-heated plate (traditionally of copper) while the other side of the wall is exposed to cold, provided through water-cooled plates. The *guarded* hot-box, shown in Figure 2, differs from the traditional hot box in the etching of a square into the heated plate, to a depth nearly equal to that of the plate itself (Zarr, 2001). This produces a marked reduction in lateral heat flow in the conduction of heat through the hot plate allowing the assessment of conductivity within a clearly defined and controlled space.[34]

[34] Another perspective on the benefit of the guarded hot box approach identifies the added precision gained through removing the slight resistance encountered at the edges and surfaces of a tested material as an important contributor to the increased precision off measurements.

3.5.1 Computer-assisted Simulations, PRISM

Employing computers to generate simulations of a given building's energy consumption is a fairly common practice today yet transitioning the existing engineering[35], a product of field work, numerous computations calculated by hand, invention, rules-of-thumb, etc., that evolved over decades, to a system employing a computer to perform many of those functions is a slow process. The computers calculate material and building performance by assigning values to said materials and building.

The work of Tamami Kusuda, among many others, pioneered the way toward using computers to aid in energy consumption projections (Jenkins, 2011; Kusuda, 2001; IBPSA NEWS, 2004). While working under Professor Threlkeld at the University of Minnesota, Kusuda received in-depth exposure to thermodynamics and heat transfer theories, including "psychrometrics, advanced refrigeration cycles, solar energy, transient heat conduction through multi-layer walls, etc. All of these analyses were very much relevant to computer simulation in later years…" (Kusuda, 2001). Kusuda continued to push the developing field of computer modeling: one of the earliest utilizations of a computer (a Bendix G-15, used to deliver numerous predictions on the behavior of hot-air originating from heated coils); co-authoring the first ASHRAE paper relying on computer-derived computations of pressure allocation in the performance of a multi-cylinder refrigeration compressors; and in modeling the fluid mechanics of air with a sealed nuclear fallout shelter and more (Kusuda, 2001).[36]

Regardless of the arena in which it takes place, estimation is a delicate thing, and estimating energy usage by a building is no exception. With inputs ranging from building envelope integrity, to appliance energy efficiency and consumption, to insulation, to occupant behavior, there are a host of factors whose inclusion or exclusion can dramatically impact or alter a given energy usage estimate. Yet few factors have a greater impact than weather, and it was the

[35] This refers to the late 1950's.

[36] A copy of *"A Tribut to Dr. Tamami Kusuda 1925-2003"* , from the *ibpsa*News v. 14 edition is available in Appendix D.

capacity to successfully incorporate weather data into an energy modeling program that made PRInceton Scorekeeping Method (PRISM) rather unique.

Introduced in 1985 yet originating in the early 1970s, PRISM incorporated two inputs, utility billing analysis (to gauge past energy usage) and weather data (to aid in explaining instances or periods of unusually high rates of energy consumption). This approach is very useful when dealing with existing buildings because there is existing data on energy consumption and abnormal usages due to weather can be adjusted. The PRISM model, depicted in Figure 3, broke from the mainstream pattern of making predictions based on calculated material performance under ideal circumstances while neglecting inputs from imperfections in construction and installation, weather, etc.; this structure is employed by many modeling programs today.

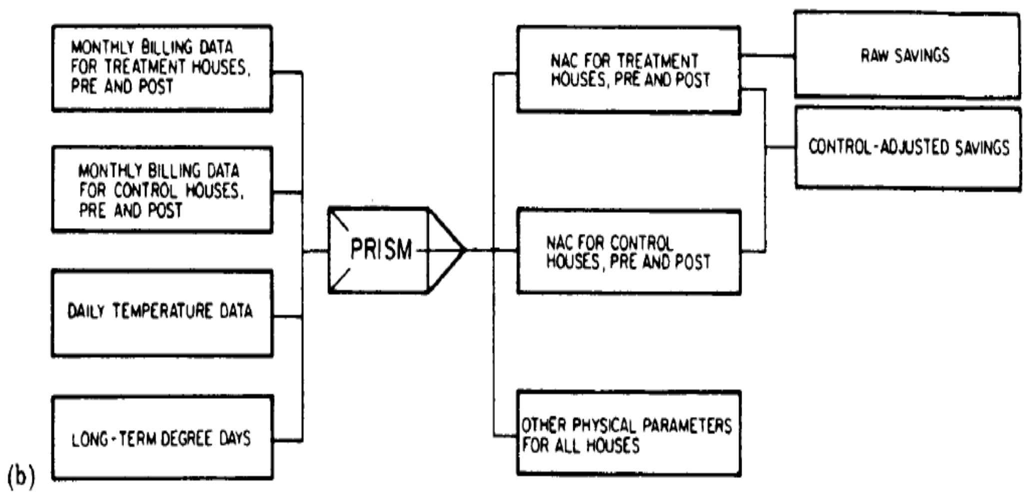

Fig. 1. Schematic diagram showing the data requirements for the Princeton Scorekeeping Method (PRISM) and the estimates that result from it: (a) the basic procedure for one house; and (b) the procedure for calculating control-adjusted savings for a group of treated houses.

Figure 4. Schematic of PRISM model and operation

Additional breaks from tradition include an emphasis on delivering a system wherein current consumption is compared against prior usage as opposed to predicting future usage, a figure based on utility billing, on real consumption, on recorded climatic data, and the inclusion of control houses during the experimental/developmental stage of the program.

CHAPTER 4: METHODS

4.1 Utility Billing Analysis

Minol U.S. delivered utility billing data for 2,276 housing units (located within the six identified communities on JBLM) for 23 monthly periods beginning January 14, 2009 and running through December 15, 2010. Physical parameters of the housing units in question came from both Minol and EQR. Puget Sound Energy provides natural gas service and Tacoma City Light provides electricity to JBLM. Table 1 provides some basic characteristics for each of these communities.

	Units	Typical Square Feet	Typical Vintage	Gas Hot Water Heat (units)	Electric Hot Water Heat (units)
Beachwood	512	1220-1494	1959-1963/ 2003	129	383
Broadmoor	169	1900-2844	Pre-1950	72	97
Davis Hill	433	1154-1262	1959-1963	224	209
Discovery Village	458	1700-2062	2005-2007	458	0
Miller Hill[37]	34	1780-2062	2008	34	0
Evergreen	147	1464-1580	1984/1995	147	0
New Hillside	523	1220-1378	1959-1963	0	523
Total	2276	-	-	1030	1212

Table 1. Community Characteristics

[37] Miller Hill is a subset of Discovery Village and therefor the hot water heater types are incorporated into The Discovery Village listing.

Our[38] analysis of the billing data consisted of three stages, the first being aggregate monthly energy statistics for 23 monthly periods for each community. To calculate monthly usage, meter readings from the beginning and end of the particular period were tallied for each unit within in a given community while statistics were calculated for all the units within a given community for that period.

The second stage of data analysis consisted of aggregate annual energy statistics for each community. These annual periods begin with the annual period ending on January 14, 2010 and end with the annual period ending on December 15, 2010. Annual usage was calculated from the beginning and ending meter readings for an annual period per each unit in a community and statistics were calculated for all the units in the community for that annual period.

In order to complete these two stages of analysis, the data required several stages of filtering and organization. The initial stage addressed a variety of abnormalities, such as estimated readings[39], fluctuations in occupancy status, utility meter roll-overs, off-sets for those roll-overs, and distinguishing those units with natural gas-fueled hot water heaters for those with electric hot water heaters. Once initial organization and filtration occurred, the data traveled to the programming department with Washington State University Energy Program where the data received comprehensive cleaning, sorting, and organization.

Finally, a regression analysis of baseline energy usage by unit was performed by Michael Blasnik of Blasnik & Associates. Mr. Blasnik's work provided a more realistic assessment of the houses, both individually and communally[40], by extracting baseload (space heating, water heating, and lighting)

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[38] "Our" refers to initial efforts by Luke Mattheis, and to consequential efforts by Rick Kunkle and Vince Schueler of WSU EE.

[39] Generally speaking, the estimates were arrived at by averaging the month prior to the missing month with the next available reading. The hardware is somewhat antiquated and transmits the readings wirelessly from individual house to neighborhood hubs. However, the transmission requires line-of-sight to function, and when line-of-sight is not available, there is no reading for that month.

[40] Time constraints prevented engaging our initial plan of using the weather-normalized data to select community-representative houses. However, the differences in power consumption between houses within a given community are relatively slight and little impact to data accuracy is anticipated. We therefore chose the houses on a basis of availability.

electricity and natural gas consumption and normalizing this data set for fluctuations in weather, using Typical Meteorological Year 3 (TMY3) information.

Essentially, the regression considers the spread of various data points, looks for a pattern within that spread and establishes the pattern that best fits the data. The X & Y axes are used to find specific pieces of information. By incorporating patterns representing heating degree-days (HDD) and cooling degree-days (CDD), acquired from TMY3 weather data, the data is adjusted to reflect what a true average would be. Essentially, the regression analysis allows one to separate the energy use due to a leaky house.

The regression model fits the equation:

$$\text{Use/day} = \text{baseload/day} + \text{heating slope} * \text{HDD/day}$$

This reduces the impact of incidental energy use from consumer electronics & other energy-consumptive devices on the summative energy use for the house. By focusing on the performance of the residential structure and the primary appliances (furnace, water heater) rather than the choices of the occupants, a more accurate representation of the overall efficiency is delivered.[41]

The utility billing analysis provides essential background for the field testing and for the computer modeling. With the results of the billing analysis in hand, the examination and analysis of individual houses can be compared against the characteristics of the surrounding community. This comparison is necessary because it establishes the house in question as representative of the greater surrounding community and with so few houses tested, the relationship between the individual house and the community becomes very important. This comparison is necessary because it establishes the house in question as representative of the greater surrounding community; tables 5 and 6, found on pages 69 and 70 illustrate that relationship.

[41] Formulas are courtesy of Michael Blasnik

4.2 Field Testing

Field testing provided a variety of information ranging from air infiltration rates, to duct leakage rates, condition of the exterior and the interior, appliances, notable repairs, and items or circumstances in need of repair. Houses were selected on the basis of condition and availability. While less than ideal, the method of selection delivered houses with average energy usage and representative physical conditions.

4.2.1 Blower Door Testing

We[42] performed full energy audits, including blower-door tests, Leakage-to-Exterior tests, and physical & visual inspections of the exterior, interior, heating and cooling systems, and appliances. A blower-door test, pictured in figure 4, is used to establish the tightness of a given structure's building envelope and is conducted by placing an industrial-strength fan in an open exterior door within a nylon sheath fitted to the door frame (creating a rough air barrier). Connected to the fan is a manometer, a device used to measure pressure. Once activated, the goal is to either pressurize or depressurize the building, while recording the volume of airflow required to achieve the desired pressure level. In general, the tighter the building envelope, the lower the volume of air passage through the fan; conversely, the leakier the building envelope the higher the airflow and the harder the fan must work to maintain a give pressure.

[42] "We" refers to Luke Howard of WSU EE and Luke Mattheis.

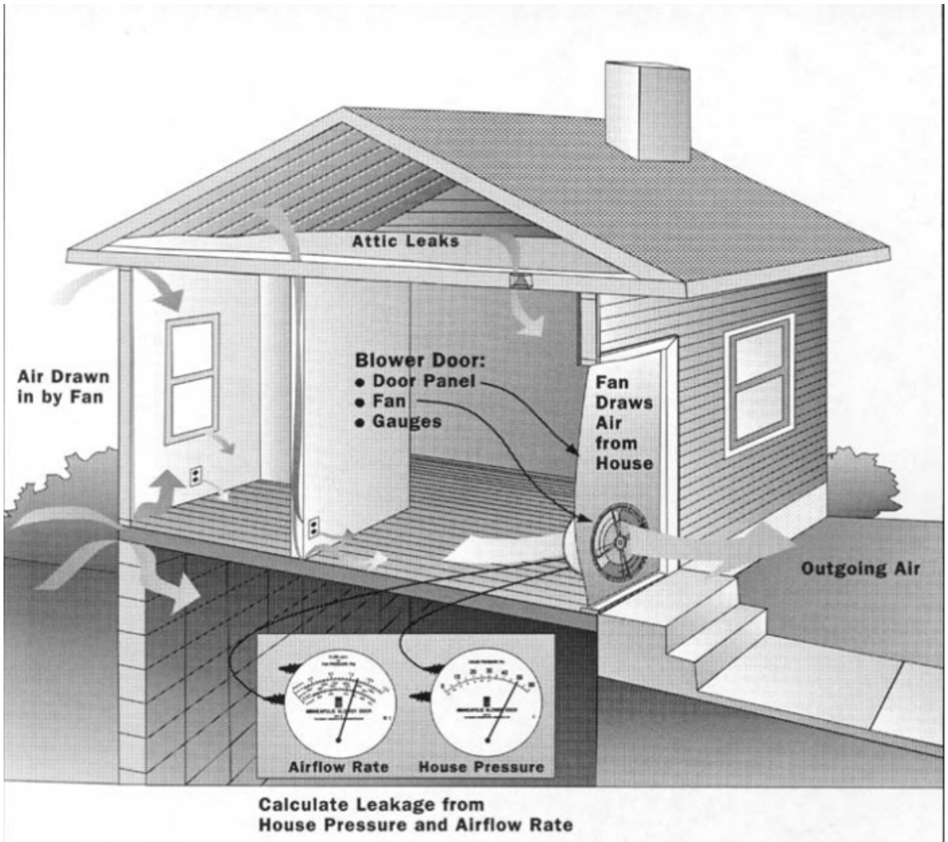

Figure 5. Schematic of blower-door dynamics

(The Energy Conservatory, 2011)

Several metrics are used to describe air movement and infiltration, however nearly all rely on a measurement delivered by the blower door: Cubic Feet per Minute at 50 Pascals (CFM_{50}). The CFM_{50} is a measurement of the (actual) flow rate of the air as it moves through the fan and with it, extrapolations to other gauges of infiltration and leakiness become possible. In this study I will use Air Changes per Hour at 50 Pascals (ACH_{50}), a measurement of how many times per hour the air within a building is exchanged for outdoor-air when the building is pressurized to -50 Pascals. Minimum Ventilation Requirement (MVR) defines the minimum level of air movement for health and air quality purposes while Approximate Leakage Area (ALA), is a calculation describing the leakage surface area where all the direct and indirect openings in the envelope combined into one large hole (Sherman, 1998; Krigger & Dorsi, 2009; U.S. DOE, 2001).

4.2.2 Duct Blower Testing

A Leakage-to-Exterior test incorporates a second fan system into the blower door test and is intended to deduce the tightness of a building's ductwork. The test operates on similar principles as the blower-door test and is conducted by first pressurizing the building (using a blower-door), then hooking a duct-blower (a much smaller version of the fan used in the blower-door test) to the duct system. If both building and duct system are brought to the same pressure, in essence to equilibrium, there *should* be no airflow between the two. The airflow that does occur goes outside through the duct system (Krigger & Dorsi, 2009).

4.3 Energy Modeling Programs

Matching the billing analysis with the audits provides the means to establish which houses are the most and energy efficient and why. Complementing the billing analysis is a secondary line of analysis in the form of energy modeling programs. The goal in using energy modeling is to estimate the energy usage of a specified retrofit measure. For example, if I want to explore upgrading the insulation in my house from nothing to high-density spray-in foam combined with blown-in cellulose, I would describe both the retrofit and the existing house to the modeling program. With all required inputs in place, the program estimates how much energy will be consumed, based on characteristics of the retrofit measure (insulation in this case) and on characteristics of the house as a system.

By modeling the various retrofit options in this fashion, I am able to establish & compare rates of energy efficiency as well as produce cost-benefit analyses. The cost benefit calculations are based on the estimated energy savings generated by the modeling software Building Energy optimization (BEopt) and include: financial saving per year and per month; cost of the retrofit measure; simple payback of the measure, in years; and the monthly savings of the measure.

By running two modeling programs on each house, the results can be compared against one another and against the utility bills. The results of this comparison provide indications of both accuracy and precision of the two programs. With this information, a) JBLM will be better situated to make better-informed decisions when faced with retrofitting other buildings as well as new construction, and b) the developers of the software programs will be able refine the operations of the modeling programs.

4.3.1 SIMPLE

SIMPLE is a spreadsheet designed by Michael Blasnik to allow the input of qualitative data to generate the estimated energy use for the house in question. The quantitative values given to the qualitative entries are drawn from extensive analyses of energy consumption from all over the country and represent averaged values of those qualitatively described inputs. For example, wall insulation is entered as “no insulation, partial/semi insulation, standard insulation, good insulation, very good/foam”; this is in place of a specific R value. However, should the user desire to enter specific values or parameters for the house, such as air leakage measurements, SIMPLE provides the user with the ability to override the standard values.

The model itself possesses neither hourly nor bin calculations, enabling the program to quickly deliver a multivariable linear regression. SIMPLE works off pre-calculated results from hourly modeling and analysis for a given weather station using TMY3 weather files. The results are summarized into key parameters that are used in a simplified engineering heat balance approach, resulting in a program geared to empirical data.

Once all parameters are entered, SIMPLE generates Annual usage Estimates for both homes, broken into the categories of Heating, Water Heating, Cooling, and All Else, and displays energy usage in terms of natural gas and electricity. Figure 5 depicts the SIMPLE interface.

Simplified Home Energy Usage Estimation Tool

v 0.9.8 © M. Blasnik 4/6/11 - Olympia WA weather station only

- Data entry in yellow cells only, lower table allows optional overriding of defaults

	Current Home		Proposed Home		Estimated Savings	
Annual Usage Estimates	Gas	Electric	Gas	Electric	Fossil	Electric
Heating	697	0	1189	0	-491	0
Water Heating	162			6378	162	-6378
Cooling		0		0	0	0
All Else	22	5586	0	9046	22	-3461
Total Usage	882	5586	1189	15424	-307	-9839
	therms	kWh/yr	therms	kwh/yr		
secondary heating use	0		0			

Weather Station	WA_OLYMPIA	Copy Current Home

House Characteristic	Current Home	Proposed Home
Finished floor area (above grd	1560	2424
Stories	1	2
Bedrooms	2	4
Primary Heating Fuel	Gas	Gas
Heating System Type	High Efficiency	Older
Heat Distribution Type	Forced Air / Ducts	Boiler / Radiators
Wall Insulation	Std Ins	Std Ins
Attic Insulation	Some Ins	Some Ins
Window Type	Single	Single
Window Area	Typical	High
Air Tightness	Average	Leaky
Foundation Type	Slab	Basement
Foundation Insulation	None	None
Ducts: % in Attic	95%	0%
Ducts: % in Slab	0%	0%
Duct Leakiness	Leaky	Leaky
Duct Insulation	Std (R-4)	None
Cooling Info		
AC SEER (none=0)	0	0
Window Shading	Typical	Typical
Cool Roof / Rad. Barrier rafter	Std Color	Std Color
Water Heating Info		
Water Heater Fuel	Gas	Electric
Water Heater Type	Standard	Standard
Hot Water Fixture Efficiency	Average	Average
All Else Info		
Lighting Efficiency (W/sqft)	Average	Average
Primary refrigerator	Average	Average
Extra Refrigerators / Freezers	None	None
Entertainment (TVs & PCs)	Average	Average
# Other Large Uses (500 kWh	0	0
Other Plug Loads	Average	Average
Clothes Dryer Fuel	Electric	Electric
Cooking Fuel	Gas	Electric

Occupancy & Behavior		
Occupants, if kn	2	6
Heating Setpoint	70	68
Cooling Setpoint	76	76
Lighting hours/d	Average	Average
Shower Use (tin	Average	Average
Clothes Dryer Us	Avg	Avg
Laundry Use (He	Average	Average
Other Hot Water	Average	Average

Secondary Systems & Components		
Secondary Heat	None	None
Secondary heat	0%	0%
Wall Type 2	Std Ins	Std Ins
Wall Type 2 - %	0%	0%
Attic Type 2	Some Ins	Some Ins
Attic Type 2 - %	0%	0%
Window type 2	Dbl/Sgl&Storm	Dbl/Sgl&Storm
Window Type -	0%	0%

Figure 6. SIMPLE data entry screen

4.3.2 BEopt

Developed by the National Renewable Energy Laboratory (NREL), *BEopt* predicts the amount of energy usage for a given building based on the building's characteristics such as age, dimensions, construction style & method, utility rates & type of heating fuel, orientation of the house, occupancy, appliances, and occupant behavior, generally speaking. The software user identifies and selects these characteristics (materials, designs, location) with known properties through a series of drop-down menus and when all selections are made, the software program estimates and the energy consumption. This occurs through the rapid calculation of energy consumption using known values, such as kWh/year in the case of refrigerators, or BTUs for water heaters; known rates of energy consumption are used to calculate the energy consumption over the course of a year.[43] The calculations incorporate the impacts of each factor on the performance of the other factors.

For example, if one replaces incandescent light bulbs for compact fluorescent light (CFL) bulbs one will save energy due the greater efficiency of the CFL. However, the heat discharged by the incandescent bulbs contributes to the overall temperature of the conditioned space. This means the furnace will need to work slightly more than before the changeover and recognizing the relationship between separate actions is a function performed by BEopt.

In this study, the primary function served by BEopt is generating energy consumption estimates for certain retrofit measures, individually and in groups. These values are matched with cost information provided by local contractors to provide economic parameters including simple payback, monthly & annual savings, and monthly & annual cash flow.

BEopt uses three main input screens to generate the predicted energy consumption, associated costs, and costs of the varying modeling options, such as increasing attic insulation to R-49. The first screen, shown in Figure 6 & referred to as the Geometry Screen, directs the user to graphically map the physical dimensions of the house, including foundation & above-surface stories, the associated square footage, and number of rooms. Within the geometry screen (as well as the Options Screen) the user can create different Cases. These function as folders within the project and contain a variety of files called Designs. Designs are files containing the different elements comprising the modeled houses and it is the selection or de-selection of these elements that create a modeled house.

[43] These values often originate with the manufacturer but also come from other testing facilities such as Lawrence Berkley National Laboratory or Oak Ridge National Laboratory

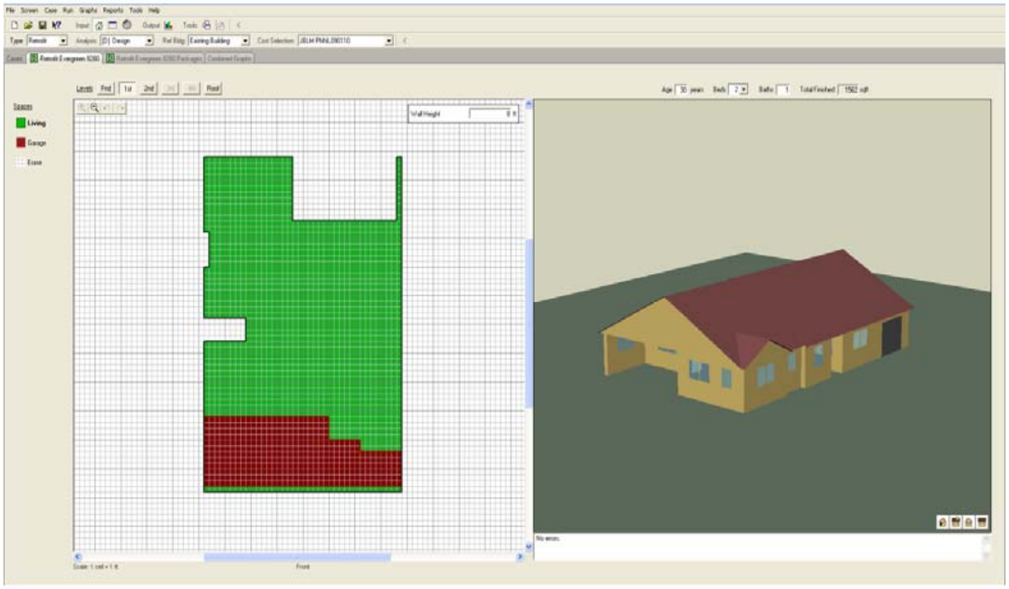

Figure 7. BEopt geometry screen, unit Evergreen 9280

The second screen, referred to as the Options Screen and displayed in Figure 7, lists the individual measures (that) comprise the finished house, organized in a cascading, collapsible menu of options. The measures include structural elements such as framing as well as appliances, building orientation, HVAC, and other relevant inputs. Once the geometric entries are made, the individual component options are selected, filling out the shell constructed by the user in the geometry screen. In the option screen, the user is able to create multiple variations of the existing house, with each variation representing a potential retro fit measure or group of measures.

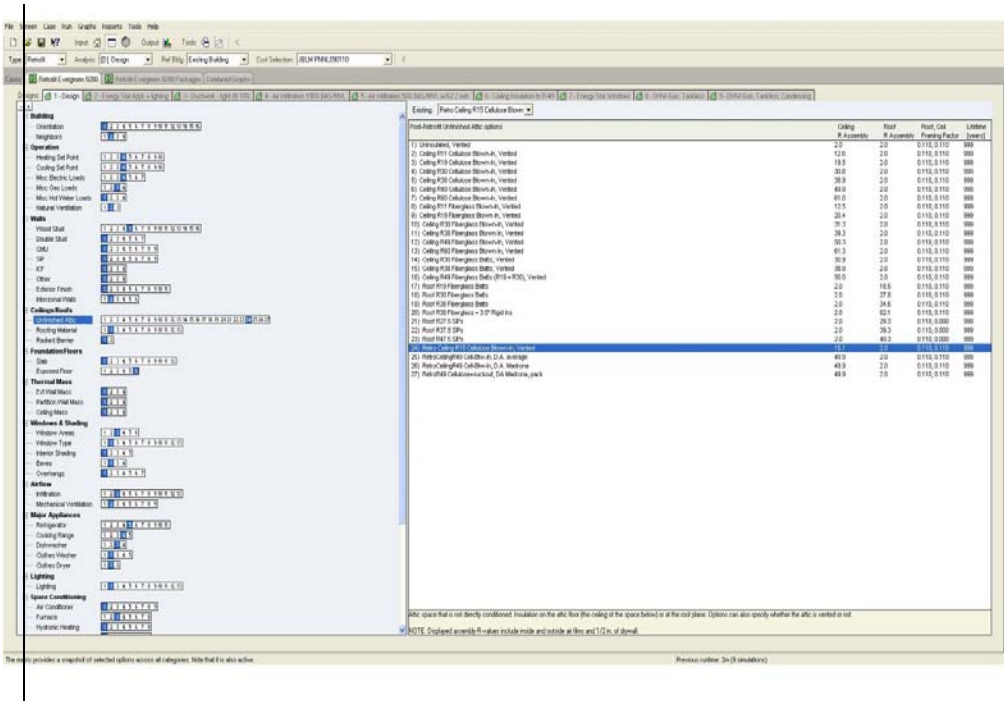

Figure 8. BEopt options screen, unit Evergreen 9280

The third screen, displayed in Figure 8 and referred to as the Economic Parameters screen, contains inputs for local energy rates, electricity, natural gas, oil, etc. It also includes inputs for mortgage rate/duration input, location, carbon emissions, and the multiplying factor used to calculate source energy consumption.

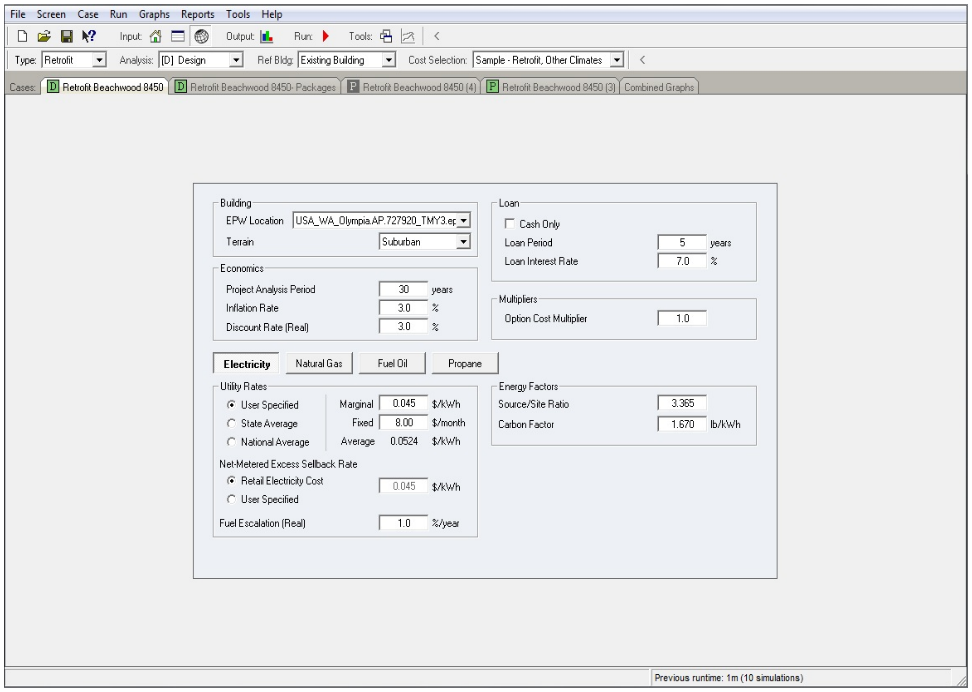

Figure 9. BEopt economic parameters screen, unit Evergreen 9280

Once all parameters are entered and the analysis run, the results are displayed on the Output Screen (pictured in Figure 9) and subdivided into three sections. One section displays the Annualized Energy Related Costs by plotting the reductions in energy usage against the energy-related cash flows for each design, allowing the user to determine which design produces the greatest energy savings and the price of those savings. Another section provides a graphic and numerical accounting of energy usage by the selected parameters of the modeled house, the HVAC system, lighting, heating, appliances, etc. This accounting can be viewed in terms of utility bills, CO_2 emissions, source energy, and site energy, divided into electricity, natural gas, propane, and heating oil. The third section provides a visual comparison of what elements of a given design differ from the original model, the existing house, the percent energy savings and cost of the respective measure.

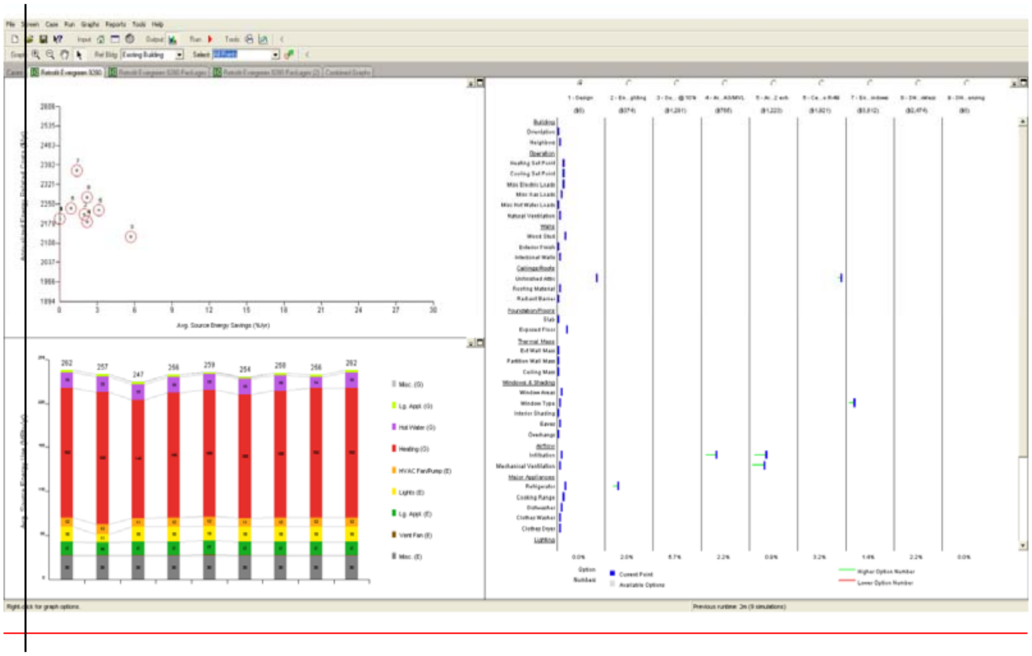

Figure 10. BEopt output screen, featuring the unit Evergreen 9280

BEopt was engaged by creating a base case model for each audited house, using the measurements, structural, and compositional elements observed during the audits as well as from data sent from EQR. Compared against the base case are the modeled retrofit measures, with one variation (the retrofit measure) per design. The package retrofit modeling operated under identical circumstances, with each package compared against the base case as described by the energy audits and EQR. Plotting the retrofits in this fashion enables the user to compare the costs and benefits of each measure, both in terms of energy use and in finances, to identify savings opportunities

4.4 Practical Feasibility

While cost is a primary factor in the cost-benefit evaluation of these retrofit measures, other factors need to be considered when evaluating the retrofit measures. For example, can the measure in question be applied to all houses on JBLM? What impact does time have on a retrofit measure? Does the measure require special training or tools to implement? What pricing structure exists? Can a retrofit measure be modeled within a reasonable range of complexity? While a given retrofit measure may present superior energy or financial savings, if its implementation is not feasible, the savings offered become moot. The practical feasibility of certain measures will be further examined in section 5.3 on pg 55.

CHAPTER 5: DATA & RESULTS

(Utility billing analysis draws heavily on work performed by Rick Kunckle)

5.1 Utility Billing Analysis

Utility billing analysis reveals several patterns within the 6 communities studied. One such pattern is the modest amount by which both individual houses & communities differ in energy use. Other patterns are visible when comparing houses built before Washington State adopted an energy code. For example, those houses constructed prior to 1977 (the year of the initial energy code adoption) underperform houses constructed after 1977. Subsequent, updated editions of the code were released in 1984, 2001, and 2009, and with each edition the basic standard for insulation, building envelope tightness and other elements of energy efficiency grew. The houses within the Discovery Village/Miller Hill community are of 2005-2007 vintage, and easily outperform older houses. This is due in part to increases in materials technology and to the wear associated with age, however the obligation to use these technologies is, in large part, the result of code evolution.

Billing analysis also served to identify water heaters as a distinguishing factor when comparing energy usage among houses or communities. Natural gas-fired water heaters use, in general, less energy than electric-fired water heaters. While this statement leads into the complex arena of source energy vs. site energy, the basic premise is the generation and transportation of electricity is a rather inefficient process while the transportation and combustion of natural gas is comparatively *more* efficient.

One community, Davis Hill, demonstrates this disparity in efficiency well due the mixed composition of natural gas water heat and electric water heat. Within the community, houses with electric water heat used an average of 14.4 MBtus/year less than those houses using natural gas water heat, however there are 15 fewer units using electric water heaters.[44] Because electric water heaters utilize energy more efficiently (than gas-fired models), this difference is expected. Considering the low rate of efficiency in the generation and transmission of electricity, however, natural gas remains the preferable choice. This choice is preferable when considering the broader impact of electricity generation, the production of CO, CO_2, mercury, and particulates in the case of coal-fired power plants. However, such a perspective may not hold among homeowners or property managers, who may find advantages such as lower monthly costs, in pursuing electric services.

Comment [LM1]: Howz 'bout this?

Comment [LM2]: preferable to policy maker may differ from preferable to householder or property manager. I'd at least mention that here, and whether there's a divergence of perspectives on this point.

Comment [LM3]: This is….?

Within the Discovery Village/Miller Hill community, a baseload difference of 51 therms (22 percent of natural gas baseload) was established between two series of houses with identical floor plans and construction. The difference between houses lies in the type of water heater: the higher-use homes had standard water heaters while the lower-use homes used tankless water heaters. However, the houses with tankless water heaters numbered 34, making for a rather small sample. Because of this, drawing too many conclusions from this particular finding is must be approached with caution.

5.2 Field Testing Results

5.2.1 Field Audits

The field audits both describe the status of the buildings and provide measurements with which to gauge a building's energy efficiency. Key among these measurements is the blower door test and to a lesser extent, the leakage to exterior test. The results of the blower door tests placed houses into one of three classifications, 50% of Minimum Ventilation Requirement (MVR; 3.5 ACH_{50}),

[44] Additional details/data are available in Appendix A.

100% of MVR (7.1 ACH_{50}), and 150% of MVR (10.5 ACH_{50}).[45] Seven of the 12 audited houses delivered CFM_{50} tests ranging from 11.15 to 12.95 ACH_{50}, while the remaining five tested between 9.87 and 10.46 ACH_{50}.[46] These results do not specify *where* the leaks are, however by calculating the Approximate Leakage Area (ALA), an estimate of the aggregate size of the leaks is obtained. The average ALA of the houses tested is ~220 square inches, excepting the historic Broadmoor homes whose ALA average ~416 square inches. The historic Broadmoor houses have notably larger square footage so this is not unexpected.

Field audits identified several areas for improvement common in most homes tested. While the housing stock on JBLM received furnace upgrades to 92% efficient condensing gas furnaces several years ago, the current state of ductwork indicates further attention is warranted. Figure 10 displays the plenum running from the air handler to the ductwork, located in the attic. While this particular example is atypical in the degree of deterioration, it *is* an example of a problem in need of a fix, and an example of the type of problem field technicians encounter.

Comment [LM4]: if it is atypical, i.e. not really indicative of the typical situation, you need to explain why you are showing it to us.

Comment [LM5]: ?

Figure 11. Furnace/utility room in unit Beachwood 8450

[45] The values are averages of the twelve houses.

[46] Results of blower door and duct testing may be viewed in Table X, Appendix C.

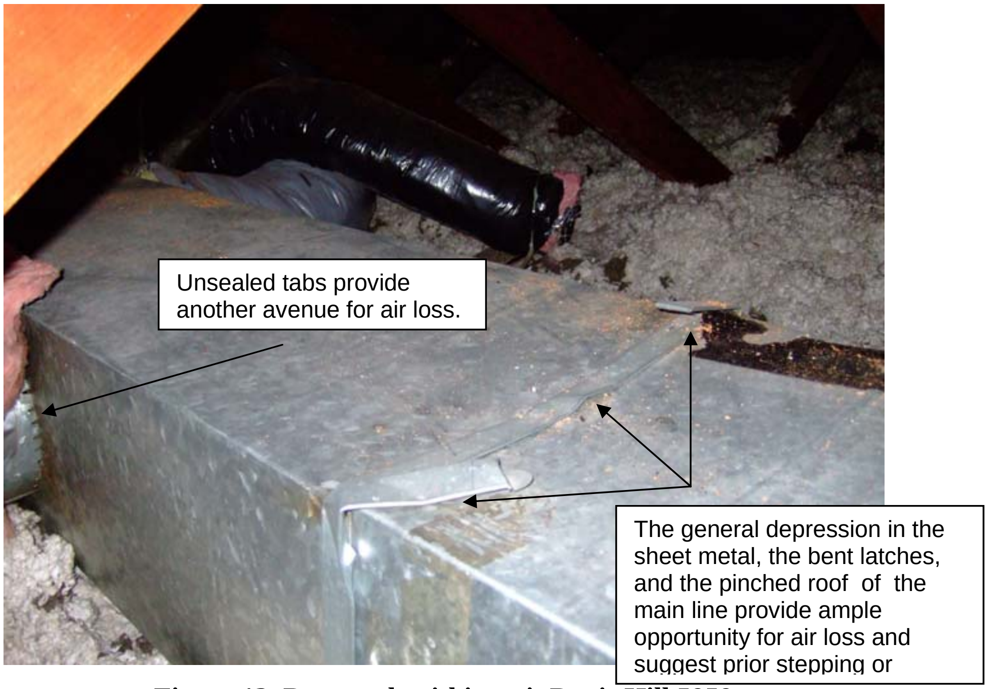

Figure 12. Ductwork within unit Davis Hill 5959

The trunk duct lines were un-insulated rigid aluminum plenums while the branch lines were flexible ducting (flex duct) as shown in Figure 11. The flex duct had 1-2” of fiberglass bat wrapped around it, roughly estimated at R-8 and protected by thick black plastic sheathing; however the junction between trunk and branch lines often was usually unsecured & unsealed. The trunk line often displayed dents, depressions, gaps between sections, and junctions sealed with duct tape (often very brittle and non-functional). In all but one community, Broadmoor, supply ductwork ran through the attic while return air entered the furnace through a vent or grill located in the wall separating the mechanical room from the living space. The space available to inspect & correct problems in the attic space is extremely limited in certain houses and helps to account for the state of ductwork. Attic insulation levels averaged ~9-12” of blown-in fiberglass, roughly estimated at R-15. In the Broadmoor community, tested houses either employed hydronic heating systems or routed the ductwork in the crawlspace beneath the building.

Routing ductwork through the crawl space will generally result in a heated crawl space *if* the ductwork is leaky and un-insulated (as is the case with this ductwork). If the crawlspace is ventilated, the conditioned air will move to the exterior. If the floor of the house is un-insulated, some of the heat will migrate to the space above. Finally, a conditioned crawl space provides an attractive environment for rodents.

The audits identified several common points of air leakage: openings in the building envelope resulting from bathroom vent penetrations; doors with deteriorated or missing weatherization; and plumbing & electrical conduit passages are not sealed (running from the attic to the conditioned interior).

In addition to those areas commonly found in the communities studied, the furnace/utility room was (also) identified as a source of heat loss; however this status depends on the style of house. While the majority of utility rooms were located inside the conditioned area, several were accessed through an exterior, louvered door pictured in Figure 12. The likely cause for this was the provision of appropriate ventilation for a previous, atmospherically-vented furnace. However, with the upgrade to the 92% efficient sealed combustion gas furnaces, the vented rooms now serve to leak conditioned air to the exterior environment.

Comment [LM6]: Not usually.

Comment [LM7]: to maintain a parallel structure in the list of common points, you should start with the problem, then stick on the additional explanatory info, i.e. turn this prase around.

Comment [LM8]: Turned!

Figure 13. Utility Rooms: Louvre Door, units Davis Hill 5428 & 5959

Paralleling the blower-door results, the duct testing results ranged from a maximum of 460 CFM_{50} to a minimum of 85 CFM_{50}. When converted into a percentage of conditioned floor area leaking to the outside, the audited houses yield duct leakage rates ranging from 9-40% (indicating 9-40% of conditioned air passing through the ductwork leaks into the surrounding environment).

5.2.2 High Bill Complaints

In order to provide further background information on housing at JBLM, including occupant behavior and condition of houses while occupied, three high-bill complaint site-visits were conducted. A site visit investigates potential causes for deviant energy usage and is conducted by EQR maintenance technicians. Site visits are triggered by either occupant inquiry or by EQR's observation of high energy use. These site visits occurred in the communities of Beachwood, New Hillside & Discovery Village, and consisted of a scaled-down energy audit & occupant interview (available in Appendix C). In addition to the three occupied units visited, an unoccupied home in the Parkway development was visited and tested. The houses visited during the project had renovations performed on them (already) or had no renovation performed on them. This provided an opportunity to inspect a unit before renovation and after.

Comment [LM9]: Here is the reason why, however I am not sure if removing it would be a a more straightforward move.

The results of the audits and testing of these homes were very similar to the results from the 12 unoccupied field tested homes in this study, with virtually identical insulation levels and window types. Infiltration rates for the homes tested in Beachwood, New Hillside and Discovery Village were within 5% of the average test result. Duct testing results for the Discovery Village home was below the Northwest Energy Star Homes specification of 6 CFM per 100 square feet of conditioned floor area at 50 Pascals.[47] For the three other homes the leakage rate was higher than the average for all housing types tested within this study. At the Beachwood home, the duct system tested at 340 CFM, due to a partially

[47] From the Washington State Energy Code 2009 pg 23: "Leakage to outdoors shall be less than or equal to 6 CFM per 100 square feet of conditioned floor area", meaning the amount of air escaping to the exterior environment cannot exceed cannot exceed 110 CFM (using a square footage of 1,843, representative of those homes).

disconnected duct. The duct was reattached by Equity staff and the duct system retested at 270 CFM. Among the houses tested, the average leakage-to-exterior was 258 CFM. The New hillside homes showed more duct leakage, however no obvious disconnect or system deficiencies were identified.

Comment [LM10]:

Comment [LM11]: this is the reduction; how near or far from average for total leakage was the improved result?

In all but one case (Beachwood), results from the occupant survey showed that occupant behavior was at least partially responsible for perceived and real high energy use concerns. Examples of energy-intensive occupant behavior include maintaining the thermostat at 78°F, multiple televisions operating throughout the day, and continual use of interior and exterior lights. Balancing those behaviors are conservative ones such as unplugging appliances and devices when not in use and maintaining a low-temperature thermostat setting.

Performance testing supports that in all but one case (Discovery Village) duct system leakage is also a significant contributor to homes with higher than average consumption. In addition, pre- and post-window retrofit infiltration rates at the Parkway home illustrate the importance of installing quality windows, tightly fitted and mounted to the wall. Prior to retrofitting, the unit delivered a blower door test of 3000 CFM_{50} and after retrofitting the unit tested at 2445 CFM_{50}, a reduction of roughly 20%.

Comment [LM12]: where can we see those? and can you give us a number for this right here?

Comment [LM13]:

The results from the audits on these homes further supports recommendations based on the unoccupied home audits. Air sealing of both the envelope and the duct system should be the highest priority, and increasing insulation performance in attics should be performed in conjunction with air sealing.

Additionally, recommendations for the Parkway development go beyond those previously made for homes included in this study. The Parkway homes are built over unconditioned basements containing un-insulated and unsealed metal ducts within an exposed, un-insulated framed floor. Significant effort should be made to air seal and insulate (to R-30) the floor. Ducts in these homes are much more accessible than homes with ducts in the attics, and should be considered a high priority for renovation.

5.3 Analysis of the Modeling Programs BEopt and SIMPLE

The primary energy modeling program used in this study is BEopt, with correlating/reference data provided by SIMPLE. For each house modeled in BEopt, an alternate model exists with one variable (the retrofit measure) changed. In addition to the individual measures, packages of measures were also modeled. The retro fit measures modeled included:

1) Improve HVAC ductwork on existing .90 AFUE[48] (high efficiency) gas furnaces

b) Dense-packing[49] the historical houses located in the Broadmoor community

Comment [LM14]: what's this?

2) Complete comprehensive building envelope air sealing, to three distinct targets:
    a) Air sealing to 150% of MVR
    b) Air sealing to 100% of MVR
    c) Air sealing to 50% of MVR, with the additional installation of an ASHRAE 62.2 complaint ventilation system
3) Increase ceiling insulation from R-15 to R-49
4) Conversion of older, standard gas water heaters to tankless gas, and tankless gas condensing water heaters
    a) Upgrade from gas standard DHW to Gas Tankless water heater
    b) Upgrade from gas standard DHW to Gas Tankless, condensing water heater
5) Conversion of older, standard electric water heaters to tankless gas, and tankless gas condensing water heaters
    a) Upgrade from electric standard DHW to Gas Tankless water heater

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[48] Annual Fuel Utilization Efficiency

[49] Dense-packing refers to blowing cellulose insulation (essentially shredded newspaper treated with fire retardant) under high pressure into the wall cavity, attic, or other desired locations. By using a higher pressure, the cellulose fibers can be installed with greater density. This not only insulates against thermal bridging but helps to reduce unwanted airflow (conduction) as well.

b) Upgrade from electric standard DHW to Gas Tankless, condensing water heater

6) Replacing existing boilers with high-efficiency models at wear-out. This applies only to the historic residences with the Broadmoor community.
7) Installation of Energy Star refrigerator, clothes washer, and lighting

In addition to these individual measures, three packages were created:

A. Improve HVAC ductwork; Air sealing to 150% of MVR; and Attic insulation R-15 to R-49

B. Improve HVAC ductwork; Air sealing to 100% of MVR; and Attic insulation R-15 to R-49

C. Improve HVAC ductwork; Air sealing to 50% of MVR + installation of mechanical ventilation; and Attic insulation R-15 to R-49.

These three cost effective measures involve either alteration *to* the building envelope or an improvement in close proximity. By offering these separate measures as a package, the highest number of buildings would receive the best retrofitting for the lowest cost. Furthermore, the maximum gain in efficiency is achieved when the measures are used in concert. For example, if one installs attic insulation without air sealing the building (or at least the attic), one runs the risk of reducing efficiency though air infiltration (convection).

5.3.1 Retrofit Analysis: Cost-Energy Savings

The cost-energy savings shown here are averages of the twelve houses modeled; Appendix A contains cost-energy savings data separated into aggregate (shown), aggregate excluding Broadmoor, and Broadmoor solo. Because the Broadmoor community includes houses with architectural and structural features unique to the particular houses within that community, such as partially vaulted ceilings and conditioned cement crawlspaces as well as houses falling under historic preservation ordinances, the reductions in energy consumption and resulting financial savings will be proportionately greater in comparison to the remaining houses. Analysis of the modeling simulations demonstrate that all measures produce energy savings, ranging from 1.17 MBtus to 50.4 MBtus[50], with duct-sealing and ceiling insulation yielding the greatest. For comparison of the specific costs and savings see Appendix A.

Table 2, located on page 69, displays the projected energy and monetary savings resulting from the implementation of Package B. Averaged into the aggregate are 4 houses from the Broadmoor community; two of these houses were built in the early 20th century and are protected under historic preservation measures while the other two were built around 1960 and incorporate unique building characteristics (relative to the other buildings in the study). One consequence of the historic presentation is high energy usage, the result of a host of factors ranging from insulation to inadequate weatherization to systematic air leakage through fireplace chimneys. For example, the historic Broadmoor houses have hydronic heating, a system utilizing a boiler and a network of piping to deliver heated water throughout the house. There is nothing inherently inefficient in hydronic heating systems, however the boiler model found in these houses have an AFUE of 81% and the distribution network for the hot water is antiquated.[51]

Comment [LM15]: yes

Comment [LM16]: these are the ones you mentioned above, right?

Comment [LM17]: I'd say something like 'systematic air leakage through fireplace chimneys'

Comment [LM18]: ☺

Comment [LM19]: This doesn;t connect well with the "host of factors" list you just gave. Boiler-based hydronic heating isn't automatically an energy loser.

Comment [LM20]:

Other houses within the Broadmoor community were built in the 1970's and feature unique architectural features, such as a ceiling half of which is vaulted, half of which is a standard 8-foot high flat ceiling. This impacts calculations involving volume as well as insulation measures for the ceiling. These houses have different foundations: still cement, but with a crawlspace housing the ductwork. Because the ductwork is not insulated and is not sealed at seams and joints, energy is lost via heated air escaping through the ductwork, and

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[50] This is an exceptionally large estimated savings, due in part to the exceptional nature of the buildings. Existing within the protection of historic preservation, the initial state is such that most efforts to improve efficiency will yield strong results.

[51] The condensing gas furnaces found in the other houses studied have AFUEs ranging from 92%-95%.

through the emission of heat from the un-insulated ductwork. One effect this has is the conditioning of the cement crawlspace, which, once achieved, moderates the overall loss of energy from the ductwork.[52]

These different architectural elements generate different analytical elements between the Broadmoor houses and the remaining eight houses tested. One difference is difference in range of savings: the estimated energy savings were greater for these houses yet the initial level of consumption was also greater. Other differences include the addition of subtraction of retrofit measures deployed in the other houses; because there is no ducting in the historic Broadmoor housing, the measure dedicated to improving ductwork is not present.

Because of these differences, I calculated a separate analysis on those four houses within the Broadmoor community by themselves (Table 3), and on the eight houses outside the Broadmoor community (Table 4).

AVERAGE ESTIMATED	PACKAGE B: 2, 3b, 4
Site Energy Savings in MMbtus/year	24.8
Site Energy Savings in $/year (gas + elec)	$250.32
Cost per measure	$2,632.14
Simple payback in years =	10.5
Monthly savings in $ =	$20.86

Table 2. Cost-savings benefits for Package B averaged in aggregate

[52] A different approach to this is comparing the loss of heat from a house during mid-winter versus the loss during late spring: the smaller the difference between inside temperatures and outside temperatures, the less energy is flows from a heated space to an unheated space (otherwise known as the Second Law of Thermodynamics).

AVERAGE ESTIMATED	PACKAGE B: 2, 3b, 4
Site Energy Savings in MMbtus/year	22.7
Site Energy Savings in $/year (gas + elec)	$229.55
Cost per measure	$2,663.70
Simple payback in years =	11.6
Monthly savings in $ =	$19.13

Table 3. Cost-savings benefits for Package B, excluding Broadmoor houses

AVERAGE ESTIMATED	PACKAGE B: 2, 3b, 4
Site Energy Savings in MMbtus/year	32.2
Site Energy Savings in $/year (gas + elec)	$322.93
Cost per measure	$2,569.03
Simple payback in years =	8
Monthly savings in $ =	$26.91

Table 4. Cost-savings benefits for Package B, excluding non-Broadmoor houses[53]

5.3.2 Models and Actual Usage Comparison

The predictive ability of a model varies from case to case, but by comparing the estimates of BEopt with those of SIMPLE and ultimately against the actual energy usage, the degree of deviation can be gauged. Such a comparison can be found in Table 5.

[53] The four houses located in the Broadmoor community tested low enough, in terms of air infiltration, to exclude Package A from modeling.

Energy Usage in MMBtus				Percent Difference With Utility Billing	
Community	Utility Billing	SIMPLE	BEopt	SIMPLE	BEopt
Beachwood					
unit 8450	66.2	80.6	106.5	22%	61%
unit 8636	106.6	99.64	101.7	-7%	-5%
New Hillside					
unit 6759	118.1	87.68	112.7	-26%	-5%
unit 6768	144.3	80.66	103.9	-44%	-28%
Davis Hill					
unit 5428	91.1	85.25	108.4	-6%	19%
unit 5959	119.5	98.65	131.2	-17%	10%
Evergreen I					
unit 9280	78.6	110.76	81.9	41%	4%
unit 9290	90.9	105.92	139.5	17%	53%
Broadmoor					
Historic, 2309	209.4	186.65	238.6	-11%	14%
Historic, 2351	278.7	198.82	236.5	-29%	-15%
unit 2651	102.9	96.49	208.2	-6%	102%
unit 2652	90.8	95.79	152	5%	67%

Table 5. Results of SIMPLE and BEopt modeling vs. utility billing for field tested homes

Table 6 describes an alternative gauge of the modeling program's accuracy: comparing a modeled house against the aggregate community energy usage. Comparing the modeled energy consumption of one house against a community's provides several benefits: the impact of fluctuations in energy usage resulting from occupant behavior is greatly reduced (assuming one is interested in communal-scale energy usage); the ability to factor in DHW fuel type when comparing individual houses to communities; and the larger sample size of the community *en masse* produces results with a higher degree of confidence.

Communities with Electric Water Heat	Mean Energy Use in MMBtus	Unit Number	SIMPLE Projections in MMBtus and %	BEopt Projections in MMBtus and %
Beachwood	86.8	8450	80.6 (-7%)	106.5 (22.7%)
		8636	99.6 (15%)	101.7 (17%)
New Hillside	97.7	6759	87.7 (-10%)	112.7 (15%)
		6768	80.7 (-17%)	103.8 (6%)
Davis Hill	91.5	5428	85.3 (-7%)	108.4 (18%)
Communities with Natrual Gas Water Heat	Mean Energy Use in MMBtus	Unit Number	SIMPLE Projections in MMBtus and %	BEopt Projections in MMBtus and %
Davis Hill	105.9	5959	98.7 (-7%)	131.2 (24%)
Evergreen I	96.7	9280	110.8 (15%)	81.9 (-15%)
		9290	105.9 (10%)	139.5 (44%)
Broadmoor, historic	245.3	2309	186.7 (-24%)	238.6 (-3%)
		2351	198.8 (-19%)	236.5 (-4%)
Broadmoor, 1960's vintage		2651	96.5 (-61%)	208.2 (-15%)
		2652	95.8 (-61%)	152.0 (-38%)

Table 6. % Deviation of SIMPLE and BEopt from community mean energy usage

Modeling programs are useful tools when gauging the behavior of an unoccupied building under a given set of conditions and for detailing how the building uses energy. However, using *only* models to predict the energy usage of an existing, occupied house must be approached with some caution. The models calculate what *should* be the gas or electric usage in this house under steady, relatively static conditions; in other words, the modeling program operates under a set of assumptions and the more sophisticated the program, the greater and more complicated the assumptions. When the basis for those assumptions is challenged by unforeseen occurrences (occupant behavior, for example), the assumption the precision and accuracy of the modeling program suffers. The assumptions can be adjusted to reflect what the expected behavior is, but it is guesswork, to some degree. For example, included in the modeling analysis is the ability to set a background temperature. EQR sets the thermostat at 72°F for unoccupied houses however I used the Department of Energy-sponsored Building America program benchmark of 71°F, a representation of the official estimate of an average household's baseline thermostat setting.

In this situation, the billing analysis and field testing provide as much information to the modeling program as possible and are useful when considering the proposed energy consumption delivered by the program. Are the estimates reasonable, based on what (we) know of environment? If the answer is "no", the inputs are double and triple checked for data-entry errors. While the differences in energy usage between individual houses can be ascribed, to a certain extent, to occupant behavior, when observed on a community-wide level, the impact from an individual occupant's behavior can be mollified. Further discussion of occupant behavior occurs in section 6.

5.4 Practical Feasibility

After running the models and reviewing the projected costs and benefits, I scrutinized the retrofit measures for other obstacles or complicating factors that might arise. Measure 1b, dense-packing insulation, produced excellent energy savings, as did measure 6, upgrading existing boilers to high-efficiency models. However, these measures would apply to a very small group of houses. The likelihood of pursuing measure 6 decreases further upon consideration of the recent installation of new boilers.

When approaching measure seven, upgrading existing lighting and certain appliances to high-efficiency models, several complications arose. Most houses on JBLM have both florescent and incandescent lights; determining the percentage of one type would be rather difficult and the process of determination would be prone to errors and far-reaching estimations. Of greater impact to this measure is the ever-evolving state energy code, because, as time passes and the requirement for energy-efficient lighting and appliances becomes law, installing energy efficient appliances and lighting will be required. In addition, nearly all existing dishwashers are Energy Star and clothes washer/dryer units are owned & installed by the occupant, further complicating both the formation and the eventual implementation of said measure.

Balancing these drawbacks is the position of EQR as an entity that can *recommend* the purchase of an energy efficient appliance (clothes washer) to the residents. Establishing a relationship with large retail distributor or other commercial entities with the ability to provide reduced price on units could provide more residents on JBLM the opportunity to heed that recommendation.[54]

The installation of U-0.30 windows was considered as a potential measure for analysis, however several obstacles rendered windows as *in*feasible very early on: the lack of a clear pricing structure; an existing population composed of both functional and non-functional windows; and the in-depth series of customizations within the modeling program required for model rendering possess a high potential for error. Thus, it was not considered to be practically feasible.

CHAPTER 6: EXOGENOUS VARIABLES

Weather conditions and occupant behavior are two exogenous factors with substantial impact on the results of this analysis. Weather is the primary driver behind weatherization and retrofitting: insulation from the undesired outdoor elements. It impacts nearly every aspect of daily life, is a dynamic force able to buck any given behavioral prediction, and will ultimately dictate the evolution of

[54] EQR *can* recommend the purchase of an energy efficient appliance to the residents; in a similar vein, establishing a relationship with large retail distributor or other commercial entity with the ability to provide reduced price on untis.

the NW over the coming years. Should the average temperature rise, the Pacific Northwest will lean toward a cooling environment: weatherization and retrofitting will aim to retain cooled and dehumidified air. Should the summers become hotter and winters cooler designs will need to accommodate that greater fluctuation. Should the annual snow pack and snow melt lessen or become more volatile, houses may require a much greater degree of efficiency in the use of all resources.

The heart of the matter is control; we have absolutely no control over the weather and must therefore rely on reducing the impact of the uncontrollable on our comfort level. While the weather itself has a minor impact on the functioning of my recommendations, it affects the behavior of a house as a system. An increase in humidity, for example will lead to swelling of wood members and increase the likelihood of mold, but will not reduce the importance of tight ductwork or attic insulation. While the weather will not impact the importance of my recommendations, it will substantially affect occupant behavior.

Occupant behavior is a quality than can be guided, through incentives & disincentives, educational outreach, etc., but not controlled. Spontaneity, medical conditions, forgetfulness, personal preferences, distractions and reactions to stimulus originating from an infinite number of possible circumstances make accurate prediction of behavior rather difficult. Impacts of occupant behavior include the preferred thermostat settings; length of time lights are left on for; number and type of personal electronic devices[55] and duration of use; and maintaining a clean furnace filter. All these factors contribute to the overall energy consumption.

Generally speaking, one factor influencing on an occupant's behavior is monetary accounting for energy usage; lower energy use = lower bills. However, on JBLM there is no per-kWh fee or other method of accounting, except when the occupants consume 30% above or below the encompassing community's mean energy use.[56]

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[55] A radio vs a new video game console or plasma TV.

[56] Above the communal usage = fee; below the communal usage = dividend.

A tangential impact of the no-fee system employed on JBLM is the relative difficulty in comparing the findings or methodology of this report to other studies. On a community-wide scale, this difficulty can be assuaged by the averaging of statistics: given that all members of these communities participate in this (billing) system, its significance as a variable within the broader JBLM community is slight. Comparing small sample sizes or individuals, however, is quite difficult due to the difference in behavior engendered by financial incentive.

CHAPTER 7: CONCLUSIONS & RECOMMENDATIONS

7.1 Conclusion

Joint Base Lewis McChord houses more than 4,900 opportunities to conserve energy within the residential sector. By applying the strengths of utility billing analysis, field testing, and energy modeling in unison, a thorough analysis of the potential gains from installing retrofit measures within the residential sector of JBLM is produced .This study indicates several measures (that) when implemented either independently or in concert can deliver significant reductions in energy consumption. These measures include air sealing, increasing attic insulation level to R-49, rehabilitating ductwork, and exchanging standard (tank) water heaters for tankless water heaters at wear-out. It is important to recognize the impact of the existing managerial infrastructure on the applicability of these recommendations on JBLM as unseen restrictions or policies may well obstruct the implementation of a given measure.

Comment [LM21]: notice that your work includes tacit assumptions about the institutional side of installing retrofits, not just the house by house physical side. Some measures aren't considered because they would be difficult to implement within th eproperty management structure that exists. This is not a flw in your work; it's just a background feature of it. But it's worth noticing.

Comment [LM22]: not quite the right word - 'level' would be better. Also it's R-49 in roofs, right, not all over. Should mention that.

Comment [LM23]: How about this?

Several factors lead to the exclusion of measures 1b, 6, and 7. Measure 1b, dense-packing the Broadmoor historical houses, produced excellent savings but was excluded due to its restrictive applicability: only a very small number of houses on base would qualify. Measure 6, replacing existing boilers with high-efficiency models at wear-out, produced solid savings however the number of buildings with boilers is relatively small, and because those buildings received new boilers very recently, the occasion to install new boilers in the near future is not expected to arise. Furthermore, the historic Broadmoor houses have a unique (relative to the other houses in the study) option when changing the furnace or hot water appliance, which is to install an integrated system capable of performing both functions Measure 7, installation of Energy Star refrigerator, clothes washer, and lighting faced several obstacles such as the difficulty in estimating the ratio of fluorescent to incandescent lights among the housing and consequently, the potential savings that exist from moving to 100% CFL.[57]

Comment [LM24]: should be 'fluorescent'

As the state energy code continues to evolve, requirements for installing energy-efficient lighting and appliances for both new construction and retrofits will become more stringent. Furthermore, nearly all existing dishwashers are Energy Star and clothes washer/dryer units are owned & installed by the occupant.

The element of energy pricing mitigates the economic significance of these findings, however. Because JBLM receives electricity at reduced rate ($0.42/kWh), there is less monetary incentive to invest in the retrofit measures a) in the immediate future, and b) to the fullest degree possible. Off-setting the reduced incentive is the military's dedication to energy conservation. What impact this factor will have on the managerial decisions made by EQR in the future is both difficult to foresee *and* outside the scope of this project.

7.2 Identification of Problems and Recommended Solutions

The research performed in this study includes identification & recognition of several problematic elements of residential housing on JBLM. The following recommendations address those elements.

□ *Condition of Existing Ductwork.*

⇒ As service calls & occupant turnover permit, inspect ductwork for leaks, punctures, disconnections, ruptures, and any other malfunctions with the ability to divert air from the duct system. Take corrective measures (such as applying mastic to all seams), as outlined by a recognized agency or standard such as (the)

[57] Including CFL, LED, high-efficiency incandescent lighting and other forms of energy efficient lighting.

Building Performance Institute or Performance Tested Comfort Systems, and incorporate those measures into routine inspections.

□ *Bolstering Skill Sets of Maintenance Technicians*

⇒ Equip maintenance staff with an improved capacity for the identification and correction of existing or potential problems (troubleshooting) such that they will be able to properly correct any deficiency encountered. The improved capacity can be acquired through trainings, workshops, and other educational measures.

□ *Engage residents with educational programs, Occupant Behavior*

⇒ Develop and implement a program to educate residents of JBLM on energy conservation and the benefits thereof including financial, environmental, and communal. This should be pursued with a fairly broad range of approaches or themes in order to access as many people as possible. The range would include traditional forms of interaction with the residents, such as fliers, but more direct methods need consideration, if not inclusion, when appealing to such a large audience with as many relatively unique characteristics as this audience has.

□ *Addressing insufficient attic insulation*

⇒ As service calls & occupant turnover permit, increase attic insulation to R-49. Incorporate air sealing into this action, using a sealing protocol established by a recognized authority on weatherization and energy efficiency. This measure need not be exhaustive in its application to a given house; indeed, characteristics of a given house or other factors such as cost may be prohibitive to a measure.

□ *Addressing Deficient Weatherization*

⇒ Apply weatherization measures where existing measures are damaged or none exist, including: weatherizing door and window frames; sealing recessed lighting fixtures; and sealing penetrations to the building envelope.

□ *Increasing Energy Efficiency of Water Heaters*

⇒ As existing water heaters are retired, replace with tankless water heaters, depending on volume capacity of gas piping. For the present & immediate future, insulate all standard water heaters both around and beneath the unit’s body.

7.3 Discussion

Utilizing these findings offers the potential to reduce energy consumption and thereby reduce the financial expenditure (on residential energy). This outcome stands to benefit the occupants, by providing a greater level of comfort, and EQR, who receives "a fee that is based on the amount of the projects net income so any decrease in expenses, such as utilities, increased our fee proportionately" (M. Greer, personal communication, December 7th, 2011).

The reduction in energy consumption also benefits the military, which is actively pursuing energy efficiency in variety of fashions and could provide assistance, financial or labor, toward implementing these measures. For example, JBLM is dedicated to a "3% annual reduction of energy consumption intensity", beginning in fiscal year 2006 and ending with a 30% reduction by fiscal year 2015 (Rexroad APG, 2010).[58] Finally, EQR is a large company, acquiring more than $1 billion in assets during late 2009-2010 and as such could access resources not available to other parties, or secure financing at a low interest rate (Equity Residential, 2010).

Additional complications arrive in the form of state and federal rebate programs. For example, the utility providing electricity to the city of Seattle, Seattle City Light offers these rebates toward replacing an existing appliance with an energy efficient model: $50 per refrigerator as well as $30 for recycling the existing refrigerator (including pick-up); $50-100 per clothes washer; $250 for installing a heat pump water heater; and $1,200 toward installing a ductless heat pump (City of Seattle , 2011).[59]

Tacoma Power, the utility providing electricity to JBLM, offers financial assistance through rebates, zero-interest loans, and grants. One example of such

[58] This particular move to increase energy efficiency a) results from Executive Order 13423, b) established the target of based on fiscal year 2003 consumption rates, and c) requires further reduction in energy consumption intensity by 6.1 MBtu/KSF annually for the next six years in order meet the target reduction. This including energy increases made to date (Rexroad APG, 2010).

[59] These rebates must be applied for.

assistance is the offer to provide up to $3,450 toward insulating ceilings, floors and walls as well as duct sealing (Tacoma Power, 2011).[60]

Federal tax incentives are fluctuating at present as some existing offers, those addressing a majority of smaller retrofits such as HVAC, insulation and water heater upgrades, are set to expire on December 31st, 2011 and at present it is difficult to foresee if these incentives will extend into 2012. Other incentives will continue through December 31st, 2016, including geothermal heat pumps, solar energy systems, wind energy systems (U.S. DOE, Energy Efficiency & Renewable Energy, 2011).

These incentives are applicable to the residential sector; EQR may qualify as a commercial entity *in addition* and have access to the incentives offered to that sector. With the number of factors involved in this particular situation, there is considerable potential for implementing at least some of the described recommendations.

It is noteworthy to recognize the importance of implementing such measures as opportunities arise. One such opportunity was lost when the high-efficiency furnaces were installed without improving existing ductwork. Skilled labor with access to the vacant building and possessing appropriate equipment could have addressed the leaky ductwork when changing furnaces. Presently, a high-efficiency furnace heats the air more efficiently (than its predecessor) but much of that efficiency is lost when the conditioned air escapes through leaky ductwork.

CHAPTER 8: IDENTIFIED CHALLENGES

The greatest challenge in this study was the degree of organization and communication needed to conduct research, acquire field data, perform analysis, and the multitude of other functions comprising this study: Joint Base Lewis-McChord requires appropriate documentation and security clearance in order to

[60] Stipulations include: being a Tacoma Power customer; the house in question is electrically heated and built prior to 1988.

enter the base. Finding and accessing the appropriate personnel within the military and Equity Residential was often a time-consuming process and, on occasion, rather confusing. Engaging the assistance of a third party analyst who works and lives on the East coast presented some difficulty in maintaining clear communications.

Augmenting those challenges and the ensuing difficulties were the duration of this project, the sporadic & restrictive nature of the research, the scope of the project, and the number of different professions and professionals working on it.

Other challenges include matching different metrics, acquired through different sources to yield a common unit of measurement; the steep learning curve of the modeling program BEopt; sifting through 23 months of utility billing data in order to find one year's worth of usable data; constructing the analytical framework needed to produce a pricing structure; and managing such a large and often convoluted mass of data.

Comment [LM25]: as it stands, this seems like a weak ending to the document as a whole. The content is OK, though it's pretty brief about things like communication difficulties. But I wouldn't worry about that. What I would do is locate this away from the end, somewhere up in the body. That way you can finsih with your recommendations, and the positive note they provide.

Appendix A

Community	Units	Actual Annual Average (therms)	Regression Average Annual Use (therms)
Davis Hill	224	809	846
Discovery Village/Miller Hill	492	460	464
Evergreen	147	667	635

Table 1. Total natural gas use for communities with natural gas water heat

Community	Units	Actual Annual Average (kWh)	Regression Average Annual Use (kWh)
Davis Hill	224	7332	7249
Discovery Village/Miller Hill	492	8828	8854
Evergreen	147	8795	8409

Table 2. Total electricity use for communities with natural gas water Heat

Community	Units	Actual Annual Average (therms)	Regression Average Annual Use (therms)
Beachwood	383	501	482
Davis Hill	209	538	555
New Hillside	523	582	569

Table 3. Total natural gas use for communities with electric water heat

Community	Units	Actual Annual Average (kWh)	Regression Average Annual Use (kWh)
Beachwood	383	10761	10604
Davis Hill	209	11046	11248
New Hillside	523	11573	11641

Table 4. Total electricity use for communities with electric water heat

	Blower-Door Test	ACH50	Approximate Leakage Area	Leakage-to-Exterior	Leakage Fraction in Ductwork	Housing Type	Housing Vintage
Beachwood							
unit 8450	2000 CFM50	12.95	200 inches²	160 CFM50	14%	Duplx w/shared carport	1959-1961
unit 8636	950 CFM50	5.36	205.1 inches²	300 CFM50	23%	Single family, detached	1959-1961
Davis Hills							
unit 5428	1890 CFM50	12.28	189 inches²	275 CFM50	24%	Duplx w/shared carport	1960-1963
unit 5959	1525 CFM50	9.87	152.5 inches²	460 CFM50	40%	Duplx w/shared carport	1960-1963
New Hillside							
unit 6768	2100 CFM50	12.91	210 inches²	85 CFM50	7%	Duplx w/shared carport	1960
unit 6759	1800 CFM50	13	180 inches²	390 CFM50	34%	Duplx w/shared carport	1960
Evergreen							
unit 9290	2000 CFM50	10.2	200 inches²	135 CFM50	9%	Single family, detached	1984
unit 9280	2175 CFM50	10.46	217.5 inches²	212 CFM50	14%	Single family, detached	1984
Broadmoor							
Historic unit 2309	4100 CFM50	10.56	410 inches²	Hydronic Heating		Single family, detached	1931
Historic unit 2351	4225 CFM50	10.51	422.5 inches²	Hydronic Heating		Single family, detached	1931
unit 2651	2850 CFM50	11.15	285 inches²	280 CFM50	18%	Single family, detached	1959-1963
unit 2652	2800 CFM50	10.95	280 inches²	175 CFM50	11%	Single family, detached	1959-1963

Table 5. Results of blower door and duct testing, housing vintage & style

	1) Improve ductwork	2a) Envelope air sealing to 10.5 ACH50	2b) Envelope air sealing to 7.1 ACH50	2c) Envelope air sealing to 3.5 ACH50, inc. mech. vent.
Site Energy Savings in MMbtus/year	8.8	3.3	8.8	9.5
Site Energy Savings in $/year	$87.45	$144.36	$88.88	$91.82
Cost per measure	$394.24	$225.00	$879.17	2137.5
Simple payback in years	4.5	1.6	9.9	15.5
Monthly savings in $	$7.29	$12.03	$7.41	$7.65

	3) Ceiling insulation to R49	4a) Gas Standard DWH to Gas Tankless	4b) Gas Standard DWH to Gas Tankless, Condensing	5a) Electric Standard DWH to Gas Tankless	5b) Electric Standard DWH to Gas Tankless, Condensing
Site Energy Savings in MMbtus/year	8.4	5.2	7	-2.3	-0.5
Site Energy Savings in $/year	$86.98	$51.04	$68.87	$138.61	$156.39
Cost per measure	$1,424.44	$1,138.00	$1,350.00	$1,278.00	$1,490.00
Simple payback in years	16.4	22.3	19.6	9.2	9.5
Monthly savings in $	$7.25	$4.25	$5.74	$11.55	$13.03

Table 6. Cost-savings benefits for individual measures, averaged in aggregate

	1) Improve ductwork	2a) Envelope air sealing to 10.5 ACH50	2b) Envelope air sealing to 7.1 ACH50	2c) Envelope air sealing to 3.5 ACH50, inc. mech. vent.	3) Ceiling insulation to R49
Site Energy Savings in MMbtus/year	9.03	3.28	6.07	1.26	8.05
Site Energy Savings in $/year	$87.45	$144.36	$88.88	$91.82	$86.98
Cost per measure	$378.90	$225.00	$715.63	$1,734.38	$1,569.17
Simple payback in years =	4.33	1.33	7.03	11.33	18.04
Monthly savings in $	$7.29	$12.03	$7.41	$7.65	$7.25

	4a) Gas Standard DWH to Gas Tankless	4b) Gas Standard DWH to Gas Tankless, Condensing	5a) Electric Standard DWH to Gas Tankless	5b) Electric Standard DWH to Gas Tankless, Condensing
Site Energy Savings in MMbtus/year	5.19	6.97	-2.22	-0.45
Site Energy Savings in $/year	$51.16	$68.74	$136.83	$154.34
Cost per measure	$1,138.00	$1,350.00	$1,278.00	$1,490.00
Simple payback in years	22.25	19.64	9.39	9.7
Monthly savings in $	$4.26	$5.73	$11.40	$12.86

Table 7. Cost-savings benefits for individual measures, averaged in aggregate, excluding Broadmoor

	1) Improve ductwork	1b) Dense-pack historic Broadmoor	2b) Envelope air sealing to 7.1 ACH50	2c) Envelope air sealing to 3.5 ACH50, inc. mech. vent.	3) Ceiling insulation to R49
	7.93	50.35	14.16	25.91	7.58
Site Energy Savings in $/year	$74.53	$501.21	$142.83	$259.11	$78.97
Cost per measure*	$455.60	$3,001.00	$1,206.25	$2,943.75	$1,134.98
Simple payback in years	6.11	5.99	8.45	11.36	14.37
Monthly savings in $	$6.21	$41.77	$11.90	$21.59	$6.58
Monthly cost at 7% over 30yrs	$4.11	$21.01	$6.79	$10.13	$17.04
Monthly Cash Flow at 7% over 30yrs	$2.10	$20.76	$5.11	$11.46	-$10.46
Monthly cost at 4% over 30yrs	$2.81	$14.33	$4.63	$6.91	$11.62
Monthly Cash Flow at 4% over 30yrs	$3.40	$27.44	$7.27	$14.68	-$5.04

	4a) Gas Standard DWH to Gas Tankless	4b) Gas Standard DWH to Gas Tankless, Condensing	5a) Electric Standard DWH to Gas Tankless	5b) Electric Standard DWH to Gas Tankless, Condensing
Site Energy Savings in MMbtus/year	5.15	7.01	-2.38	-0.52
Site Energy Savings in $/year	$50.78	$69.13	$142.15	$160.50
Cost per measure	$1,138.00	$1,350.00	$1,278.00	$1,490.00
Simple payback in years	22.41	19.53	8.99	9.28
Monthly savings in $	$4.23	$5.76	$11.85	$13.38

Table 8. Cost-savings benefits for individual measures, averaged in aggregate, only Broadmoor

Appendix B

Hardwoods, such as oak, possess an R-value of 0.71/inch Btu/ hr while softer wood, such as white pine, have an R-value of 1.41/ inch Btu/hr (coloradoenergy.org). For reference, a modern double-paned low-E window has an U-factor of 0.4, roughly equivalent to a R-value of 3.13. The following is a listing of common materials and their respective R-values:

R-Value Table - English (US) Units

Material	R/Inch	R/Thickness
	hr·ft2·°F/Btu	hr·ft2·°F/Btu
Insulation Materials		
Fiberglass Batts	3.14-4.30	
3 1/2" Fiberglass Batt		11
3 5/8" Fiberglass Batt		13
3 1/2" Fiberglass Batt (high density)		15
6 1/2" Fiberglass Batt		19
5 1/4" Fiberglass Batt (high density)		21
8" Fiberglass Batt		25
8" Fiberglass Batt (high density)		30
9 1/2" Fiberglass Batt		30
12" Fiberglass Batt		38
Fiberglass Blown (attic)	2.20-4.30	
Fiberglass Blown (wall)	3.70-4.30	
Rock Wool Batt	3.14-4.00	
Rock Wool Blown (attic)	3.10-4.00	
Rock Wool Blown (wall)	3.10-4.00	

Cellulose Blown (attic)	3.60-3.70[1]	
Cellulose Blown (wall)	3.80-3.90[1]	
Vermiculite	2.13	
Autoclaved Aerated Concrete	1.05	
Urea Terpolymer Foam	4.48	
Rigid Fiberglass (> 4lb/ft3)	4	
Expanded Polystyrene (beadboard)	4	
Extruded Polystyrene	5	
Polyurethane (foamed-in-place)	6.25	
Polyisocyanurate (foil-faced)	7.2	

A more detailed list may be found at http://www.coloradoenergy.org/procorner/stuff/r-values.htm

Appendix C

A Short History of Thermodynamics

The National Aeronautics and Space Administration (NASA) defines thermodynamics as “The study of the effects of work, heat, and energy on a system” (NASA, 2010). This study examines several systems (individual houses and communities) in hopes of determining the existing energy efficiency of these systems and, if appropriate, offer courses of action. In other, familiar words this project studies the “effects of work, heat, and energy on a system”. This study uses thermodynamics to gauge how efficient the target system is, and the greater the understanding of thermodynamics, the greater the understanding of this study and its results.

Comment [LM26]: Is this introduction/explanation good?

To list the work on thermodynamics is, in many respects, picking up a thread from the history of Physics and Chemistry. But where does one pick up that thread? Within ancient Greece lie early records of atomic theory, attributed to the writings of Leucippus. Archimedes and Aristotle laid foundational work for much of our scientific method, as practiced today, and Hero of Alexandria described a primitive form of the reaction turbine called the *Aeolipyle* (Hills, 1989). However, Libby (1918) writes how records of Ancient Egypt demonstrate detailed understanding of metallurgy, astronomy, medicine, and other areas of highly complicated scientific study thousands of years before the Greeks. He also notes how knowledge flowed from Egypt to Greece, through the travels of individuals such as Pythagoras.

Comment [LM27]: just as important -- give readers a phrase or half-sentence about why you're taking them into this.

Comment [LM28]: When I wrote this it was with the intent of combining a literature review with a historical review of the subject matter, but it doesn't seem terribly important at this stage. I believe having historical context will always stand one in stronger stead, which is the reason I'd like to keep it. Hopefully the explanation here in the paper works…

Is it better to pick up the thread a bit later with, for example, Galileo Galilei, who is credited with producing the first thermometer, measuring temperature via the expansion and contraction of heated air (Asimov, 1991; Marschall, Maran, 2009)? [61] Valleriani (2010), however, notes pneumatic devices enjoyed utilization in Hellenistic times. Knowing this, is ascribing the beginning of thermodynamic studies to Galileo's time appropriate? What of Boyle's work on the properties of a vacuum or Newton's laws of motion?

These renowned figures and too many others to name here, all contribute to thermodynamics and to our understanding of that natural world, but in *From Watt to Clausius: the rise of thermodynamics in the early industrial age*, D. S. L. Cardwell (1971) posits (how) the study of thermal transfer originated in the early

Comment [LM29]: should be 'renowned'

[61] The term "thermometer" refers only to a device used to ascertain the air temperature, not to a particular method of measure or of constructing the device.

18th century within the fields of engineering and chemistry. Such a statement is, or course, debatable, but for the purpose of introducing the subject of thermodynamics, Cardwell's hypothesis works well. With the aid of Richard Hills, John H. Lienhard gives a figurative yet illustrative description of the steam engine's early (developmental) days and why the stream engine is viewed as an identifiable point of origin for the study of thermodynamics.[62]

The thermometer enabled one to measure change in temperature, a fundamental element in conducting experiments and research in thermodynamics. In keeping with NASA's working definition of thermodynamics, *the study of the effects of work, heat, and energy on a system*, the guarded hot-box represents one of the largest contributions to residential energy efficiency because it enables the measurement of thermal conductivity in a closed (determinable) environment. In the American Society for Testing and Materials (ASTM) Standards in Building Codes, Designation: C 1363 – 97, one finds the description "This test method covers the laboratory measurement of heat transfer through a specimen under controlled air temperature, air velocity, and thermal radiation conditions established in a metering chamber on one side and in a climatic chamber on the other side" (ASTM, 2004).[63]

The National Institute of Standards and Technology (NIST) identifies Hobart C. Dickenson as the first American to develop a guarded hotbox, in the year 1912. However, two years earlier the German researcher Richard Poensgen's

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[62] This depiction may be found on p 81 (the next page).
[63] This section is entitled "Standard Test Method for the Thermal Performance of Building Assemblies by Means of a Hot Box Apparatus".

developed his own guarded hotbox; Dickenson would later learn of this while travelling abroad through Europe, (Lide, 2001; NIST, 2011). Shirtliffe & Tye (1985) write how Poensgen developed the hotbox in 1910, yet identifies the work of E.R Metz & A. Behne and R. Bquard as influences "who both reported on guard ring applications at the 2nd International Cold Congress in Vienna in 1910". A. Berget is reportedly the first to use a guard ring, yet *he* references the work of W. Thompson, author of *Report on Electrometers and Electrostatic Measurements*, recorded in *Report of the 37th Meeting of the British Association for the Advancement of Science, held at Dundee in September 1867 (1868), London* (Shirtliffe, 1985). Identifying the lineage of apparatus such as the guarded hot-box (can) reveal the interconnectedness of scientific communities and the rate of idea and information transfer.

Comment [LM30]: I think these paragraphs could mostly be eliminated, in favor of a citation pointing to the hotbox history when you use that term in the paragraph just following these, two pages down.

A partial transcript from J.H. Lienhard's *The Engines of Our Ingenuity, No. 1686: MYSTERIOUS HEAT*:

Thermodynamics, the modern science of heat, was largely driven into being by the steam engine. It began taking its modern form just before 1700, and it finally found solid footing after 1850. The story of thermodynamics and the steam engine is really a story about theory and practice finally making peace with one another.

Historian Richard Hills helps us understand the situation. Suppose you lived two hundred years ago, and you came upon an early steam engine. What would you see? A connecting rod moving up and down in a big piston, driving a rocker arm. The far end of the arm would drive a pump or turn a wheel.

You'd see the effects of pressure. You'd see forces exerted. You'd see the effects of flowing steam. As your mind reached for analogies, you'd see something that reminded you of the familiar waterwheel. The burning coal, heating the boiler, was out of your line of sight. Heat flow was not what would catch your attention. This machine appeared to be all about pressure and flow.

So scientists struggled to see what made these strange machines work, while practical people struggled to build better engines. Most early steam-engine builders had also worked with waterwheels. Like steam engines, waterwheels turn and turn and do useful work. Waterwheels led our minds away from heat and temperature.

One inventor did take a scientific interest in heat. James Watt began as a machinist at the University of Glasgow. He experimented with heat while he talked to thermodynamic pioneer Joseph Black. Watt's greatest steam-engine invention was the separate condenser. What it did was greatly reduce wasted heat.

Further description of convection, conduction, and radiation:

Cathy Inglis: Thermal (Brickworks building products):

Conduction is the molecule-to-molecule transfer of kinetic energy (one molecule becomes energized and, in turn, energizes adjacent molecules). Eg. A cast-iron skillet handle heats up because of conduction through the metal.

Convection is the transfer of heat by physically moving the molecules from one place to another. Eg. Hot air rises.

Radiation is the transfer of heat through space via electromagnetic waves (radiant energy). Eg.Acampfire can warm you even if there is wind between you and the fire, because radiation is not affected by air.

Further description of Thermodynamics

The thermal mass effect is a combination of heat capacity and conductivity

Heat capacity –

- Is a measure of how much heat a material can hold
- Is the ratio between the amount of heat energy transferred to the object and the resulting increase in the temperature
- Specific heat is the amount of heat a material can hold per unit of mass.
- The greater the specific heat, the more energy is required to heat up the material.

Conductivity –

- Is a measure of the rate of heat transfer by conduction

Thermal resistance (R Value) -

- Is a measure of the resistance of a material to heat flow by conduction
- ie. The ease with which heat can travel through a material
- The higher the R-value of a material, the better it is at resisting heat loss (or heat gain)
- The time delay due to the thermal mass is known as a thermal lag.
- The thicker and more resistive the material, the longer it will take for heat waves to pass through.
- The reduction in cyclical temperature on the inside surface compared to the outside surface is known as the decrement factor.

Appendix D

JBLM FIELD SURVEY 2011
High Bill Complaint Field Visit
For USDOE – PNNL

Site ID#_________

Date_______________

Occupant

Name__________________________Address____________________________

_____

City, State _____________________________ Zip__________

Phone_________________

Utility (include both gas & electric) _________________________________

Electric Meter ID # ________________ Gas Meter ID # _____________

Other (wood) # cords per year _________________ (what years used)

____

Propane (propane dealer name and account #) ___________________

Person filling out this report_____________________________________

Basic Information

Home Type: double wide, single wide, other ____________ (circle one)

Floor Area: _____ ft2, Volume = ______ft3 Comments

____

Year built: _______

Mfg: ________, Model ________ Serial # _____ HUD # _________________

Super Good Cents, MAP, Energy Star, other ________________

HVAC system type, make and model #: __________________

Duct leakage results: _____ CFM@50PA to outside, _____CFM@50 total

Blower Door Test: _____ CFM@ 50PA, _____ft3 volume, _____ ACH@50 PA

DHW type, make and model #: ________________

Appliances (Energy Star) yes or no

Dishwasher: Make ______________, Model ________________

Refrigerator: Make ______________, Model ________________

Laundry: Make ______________, Model ________________

Lighting: _____% CFL (estimate)

Describe additional loads that would affect a billing analysis (well pump, welder, outbuildings, etc.): ____ __________

Plans Available: Y or N (circle one). If no: Attach a sketch floor plan with exterior dimensions.

Include Pictures & ID#: ____

Consumer Questionnaire

1. How long have you lived in the home? ______________

2. How many people live in the home (full-time occupants)? ______ Other ________________________________

3. How many people are home most of the time? _____, Ages ____

4. How many people work or volunteer outside the home at least 20 hours per week? ____________, Ages ____

5. How many people attend school at least 20 hours per week? ____________, Ages ____

6. Are any other people living in the home often not at home? Are there any other people who spend a significant amount of time at the home? Please describe other occupancy factors: ____

7. How many hours a week is nobody in the home? ____________________________________

8. How satisfied are you with the energy efficiency of your home?

Energy Efficiency: Very satisfied ______ Somewhat satisfied______ Somewhat dissatisfied_____ Very dissatisfied _______

Why do you say [insert what they picked]:

9. How satisfied are you with the comfort of your home?

Comfort: Very satisfied ______ Somewhat satisfied______ Somewhat dissatisfied_____ Very dissatisfied _______

Why do you say [insert what they picked]:

[we could specifically ask about certain aspect of their comfort – are they warm/cold; adequate lighting; noise, fresh air, healthy, etc.]

10. What one thing would you fix or repair in your home if you had the resources to do so?

11. Are there other things that need to be fixed or repaired? Please describe?

12. Have there been any significant improvements made to your home in the last 5 years? Please describe?

13. Have there been any energy efficiency (weatherization) improvements made to your home? Please describe.

14. Have you made any of the following energy efficiency upgrades (read items in the list that they did not mention in #13)

[develop list of measures we want to check]

15. **Would you ever consider purchasing a new home to replace your current home?**

Yes, enthusiastically___ Yes, with some reservations____, Definitely not_____

Please describe any benefits you think a new home would provide compared to your current home?

What things would make it difficult for you to choose to replace your current home with a new home?

Would you be able to pay any more each month to live in a new home? How much more would you be willing to pay? [we could tweak this to ask how much they think it would be worth regardless of their ability to pay?]

[We could give examples of the increased monthly payment and the potential energy savings and see if that would make any difference in their interest in a new home. However, their answer to how much they are willing to pay mostly gives us what we need.]

16. **Describe Your heating system: ____**

How often do you change your furnace filter?_______________

17. **Do you have any air conditioning? Please describe:**

18. What temperature is your thermostat set at when someone is home? winter ____ summer____

19. Do you lower the temperature on your thermostat when no one is at home or at night (when you are sleeping)? ___ yes ___ no
Describe:________________

20. Do you have a programmable thermostat? Do you program the temperature settings on your thermostat (for different days and times of days)?

Heat Pump T-stat [do we need to ask this or is programmable good enough?]

Air Quality/Ventilation

Technician's observations of odors or moisture

____None ____Odors ____Moisture

_____Mold/Mildew

Location and Description:____

____

Note any conditions which may significantly affect air quality or ventilation (e.g. smokers, solvents, aquarium):____

____

Number of full-time _______ adult occupants ______children (under 12)

Exhaust Ventilation Systems

Make and Model	Photo ID#	Location	Flow (cfm)	Daily run time (hrs)	Noisy ?	Control type*
		Kitchen				
		Master bath				
		Bath 2				
		Laundry				
		Whole House				

*manual switch, timer *(note flow measurement device used)* ___________________________

Is whole house fan operating as designed? Yes No

Location of whole house fan switch ___________________ Is switch labeled? Yes No

Note any problems (no exhaust stack, suspected disconnect between fan and termination, etc.):

____

____

Classify the **make-up air** or other type ventilation system

None	
Passive duct to HVAC return	
Dampered duct to HVAC return	
Air Inlets vents in windows/walls (circle one)	
Other	

Make-up duct diameter _______inches. Flow Rate _______
Note if the make-up damper is jammed or otherwise inoperable: ____ _____.

Do all bedrooms have pass-through vents or door undercuts? Yes ____ No_____
Room pressures > 3 Pa ? Note deficiencies and comfort issues)? If so, note here: ____ ___

Use of windows for ventilation: ____

Interior/exterior Lighting review

List each fixture type observed in the house. Include exterior lights attached to the house. Describe these fixtures as they appear when developing the lighting power for the house each of these fixtures should be represented in the fixture counts in the next section. If two fixtures are essentially identical but have different lamps then enter them as separate fixtures with separate wattage.

Where fixture descriptions beyond the generic types would be helpful the auditor can add them with the appropriate lamp and ballast information. Use the notes field to expand on the description as needed.

Fixture Schedule:

Fixture Type ID	Fixture/lamp Type[1]	# of Lamps	Ballast Type[2]	Watts/ Fixture	Field Verif	Estimated? Y/N	Notes
1							
2							

3							
4							
5							
6							
7							
8							
9							
10							
11							
12							
13							
14							
15							

[1] Use generic fixture descriptions: Incandesent, CFL, Linear fluorescent, Track light, Other

[2] Magnetic or electronic from instrument

Appendix E

A Tribute to Dr Tamami Kusuda 1925 - 2003

Photo courtesy of NIST

Through a negligent, tragic and criminal act of a drunken hit-and-run driver on 17 October 2003, Tamami "Tom" Kusuda was killed while walking across Frederick Road from the Shady Grove Metro Station in Rockville, Maryland. As our sincere condolences go out to his family and close friends, we also pause to dedicate this News issue to his life and to recall his meritorious works over his professional career.

Dr. Kusuda was born in Seattle to Japanese parents and raised in Japan. He graduated from the University of Tokyo in 1947 and returned to live in Seattle in 1950. He received a master's degree in mechanical engineering at the University of Washington and, in 1955, a doctorate in mechanical engineering from the University of Minnesota. That same year (1955), he joined ASRE, the predecessor organization to ASHRAE. As an ASHRAE member, Dr. Kusuda served on TC 4.7 (Energy Calculations), the Standards Committee, the Honors and Awards Committee, the International Activities Committee, the Research and Technical Committee, the Program Committee, TC 1.5 (Computer Applications), TC 4.2 (Weather Information), and technical committees and task groups on indoor calculations, energy requirements, survival shelters, heat transfer and psychrometrics. He received the Wolverine-ASHRAE Diamond Key Award, given for the best paper, in 1957, the Distinguished Service Award and the Crosby Field Award, given for the best paper presented at an ASHRAE meeting, in 1976. That same year he was elevated to the grade of Fellow. Later, he became a Life Member of ASHRAE and received the Louise and Bill Holladay Distinguished Fellow Award in 1987.

Dr Tamami Kusuda in Nagoya 1995 (photo courtesy of Dr Nobuo Nakahara)

Dr. Kusuda's professional career began as a staff engineer at the Worthington Air-Conditioning Company, New Jersey, during 1955-1961, where he was engaged in the development of advanced heat pumps. In 1961, Dr. Kusuda joined the Center for Building Technology at NBS (now NIST). From then through the 1970s, his research laid the groundwork for thermal simulation methods and software to follow - notably his NBSLD program, which became the industry's entry point for newer generation software, like BLAST, DOE-2 and EnergyPlus, that are used throughout the industry and the design professions today. Dr. Kusuda retired from NIST in 1986 as Chief of the Building Physics Division. While at NBS, he received the Silver (1972) and Gold (1980) medals of the U.S. Department of Commerce for his contribution to building energy analysis. Dr. Kusuda also taught in the department of civil, mechanical and environmental engineering at George Washington University, and he published over 100 technical papers in the area of building environmental design and energy conservation.

After retirement, Dr. Kusuda was a consultant to the Japan Technology Program (JTP) in the Technology Administration of the U.S. Department of Commerce. In this role, he assisted the director of the JTP in carrying out the mandates of the Japanese Technical Literature Act of 1986 to improve the availability of Japanese science and engineering literature in the United States. He was involved in all phases of these activities from the program's inception in 1987. Information thus obtained was placed into the databases at NTIS (National Technical Information Service) and the various databases of JICST (Japan Information Center for Science and Technology.) Some of the noteworthy

Dr Tamami Kusuda in Nagoya 1995 (photo courtesy of Dr Nobuo Nakahara)

Dr Kusuda with IBPSA President, Jeff Spitler at BS'99 in Kyoto (photo courtesy of Dr Jeffrey Spitler)

articles were translated and published through the Japanese Technical Literature Bulletin, a quarterly publication of which Dr. Kusuda was the editor.

Outside of his professional ties with NBS, ASHRAE, and JICST, Dr. Kusuda also committed himself to involvements with APEC (Automated Procedures for Engineering Consultants), IBPSA, and the formation of at least four international symposia (Gaithersburg, Banff, Paris, and Tokyo) on the use of computers for environmental engineering related to buildings. Most of the Charter members who hatched the idea of IBPSA in 1985 were among the participants of the well-known Gaitherburg conference in 1970, "***Use of computers for environmental engineering related to buildings***", the proceedings of which still sell for around US$99.95 (used) over the internet. The conference proceedings were a hallmark publication that many consider to be the impetus for the beginnings of IBPSA.

Dr Kusuda's creative works did not stop at retirement. IBPSA awarded him with the **Distinguished Service Award** in 1993 for his lifelong contributions to the field of simulation. He was a featured speaker at the Pan Pacific Symposium on Building and Urban Environmental Conditioning in the Asian District held at Nagoya University in 1995. He was also a keynote speaker at IBPSA's Building Simulation-1999 conference in Kyoto. His work continued into the 21st century; to wit, Kusuda, T., (2001), "Building environment simulation before desk top computers in the USA through a personal memory", ***Energy and Buildings***, Vol. 33, pp 291-302. To see his work come to an end is a big disappointment for all of us. Let me say on behalf of IBPSA, our colleagues and friends that we will surely miss the presence of Tom Kusuda at our conference gatherings. He always had valuable and noteworthy contributions to make and a friendly smile to go along with them. Truly, we will always regard him as an outstanding pioneer in the use of computer methods for analysis, simulation and design for energy efficiency in buildings.

from Larry Degelman, IBPSA Newsletter Chairperson

Bibliography

ABB, Inc. (2012). Energy Efficiency in the Power Grid. Retrieved 7 12, 2011, from The ABB Group: http://www.abb.com/search.aspx?q=energy%20efficiency%20in%20the%20power%20grid

ABB, Inc. (2012). *Energy Efficiency*. Retrieved 2011, from ABB in the United States: http://www.abb.us/industries/us/9AAC171174.aspx

Arthur D. Little, Inc. (1975). *Energy Conservation in New Building Design: An Impact Assessment of ASHRAE Standard 90-75. Conservation and Environment Buildings Programs. Conservation Number 43B.* Superintendent of Documents, U.S. Government Office, Washington, D.C. 20402. (ERIC Document No. ED140508). Retrieved July 11th, 2011, from ERIC database.

Ashrae. *Ashrae Standard 62-73R: Standards for Natural and Mechanical Ventilation*. New York: ASHRAE, 1973.

Asimov, I. *Isaac Asimov's Guide to Earth and Space*. New York: The Random House, 1991.

ASTM, (1987), *E779-87, ASTM Method for Determining Air Leakage Rates by Fan Pressurization Test*, American Society for Testing and Materials.

ASTM. (2004). *ASTM Standards in Building Codes: Specification, Test Methods, Practices, Classifications, Terminology* (41st Ed), v 2, p 1495. West Conshohocken, PA: ASTM, 2004.

Aubrecht, Gordon J. *Energy (2nd Edition)*. 2nd ed. Alexandria, VA: Prentice Hall, 1994.

Blasnik, M., Fitzgerald, J. (December, 1992). In search of the missing leak: Methods for Detecting Air Infiltration in Buildings. *Home Energy*, *9*, 27-32.

Bock, G. (Jan/Feb, 1992). Insulation for Old Houses: What You Might Encounter –Retrofit Recommendations. *Old House Journal*, vol. XX, 1, p 26-29.

Butterfiled, W.H. (Nov. 1915 to April 1916). THE COUNTRY HOME ICE-HOUSE. *Country Life in America: A Magazine for the Home-maker in the Country,* v 29, p 44. [Electronic copy]

Byers, R., Palmiter, L. (1988). Analysis of the Agreement Between Predicted and Monitored Annual Space Heat for a Large Sample of Homes in the Pacific Northwest. Ecotope, Inc., Seattle, WA; Washington State Energy Office.

Bynum, R. T. *Insulation handbook*. New York: McGraw-Hill, 2001.

Cardwell, D.S.L. *From Watt to Clausius: The Rise of Thermodynamics in the Early Industrial Age*. London: Heinemann, 1971.

Calloway, Stephen and Cromley, Elizabeth. (1991). The Elements of Style. New York: Simon & Schuster.

Cavanagh, T. (1997). Balloon Houses: The Original Aspects of Conventional Wood-Frame Construction Re-examined. *Journal of Architectural Education,* (Blackwell Publishing on behalf of the Association of Collegiate Schools of Architecture, Inc) *v 51, n 1,* 5-15.

Christensen, C., et al. (April, 2005). *BEopt: Software for Identifying Optimal Building Designs on the Path to Zero Net Energy*. Conference paper NREL/CP-550-37733, National Renewable Energy Laboratory, Golden, CO.

City of Seattle . (2011). *Appliance Rebates*. Retrieved December 2011, from Seattle City Light: http://www.seattle.gov/light/conserve/resident/appliances/

Comstock, S.W., Spanos, B.J. *Proclaiming the truth: an illustrated history of the American Society of Heating, Refrigeratin, and Air-conditioning Engineers, Inc.* Atlanta: ASHRAE, 1995.

Conceptualized reference Database for Building Envelope Research. Retrieved January 25, 2011, from http://alcor.concordia.ca/~raojw/crd/index.html

Darling, D. (2011). *coefficient of heat transmission (U-value)*. Retrieved December 2011, from ENCYCLOPEDIA OF ALTERNATIVE ENERGY AND SUSTAINABLE LIVING : http://www.daviddarling.info/encyclopedia/C/AE_coefficient_of_heat_transmission.html

Equity Residential. (2010). *Equity Residential 2010 Annual Report.* Chicago.

Degelmean, L. (April, 2004). A Tribute to Dr Tamami Kusuda 1925 – 2003. *The journal of the International Building Performance Simulation Association NEWS*, *14*, number 1.

Diamant, R. M. E. *The internal environment of dwellings*. London: Hutchinson Educational, 1971.

Ecotopia. (2011). *M. King Hubbert*. Retrieved April 13th, 2011, from The Coming Global Oil Crisis: http://www.hubbertpeak.com/hubbert/

Education Development Center, Inc. (2011*). An Impact Study of ASHRAE 90-75, Energy Conservation in New Building Design*. Washington, DC: Superintendent of Documents, U.S. Government Office. (ERIC Document No. ED140508).

Equity Residential. (2010). *Equity Residential 2010 Annual Report.* Chicago.

Eldrige, M., Neubauer, M., York, D., Vaidyanathan, S., Chittum, A., Nadel, S. (2008). The 2008 State Energy Efficiency Scorecard. ACEEE Report Number E086.

Fels, M.F., ed. (1986). Measuring Energy Savings: the Scorekeeping Approach, special issue *of Energy and Buildings, 9,* #1-2, Elsevier, Lausanne, Switzerland.

Fitzgerald, J., Nevitt, R., Blasnik, M. (September, 1994). User-friendly pressure diagnostics. *Home Energy, v11,* 19-24.

Gaynor, J., (1976). Nineteenth Century Architectural Insulation: Zoar, Ohio. *Bulletin of the Association for Preservation Technology*, 8(4), 101-112.

Gross, G., Pielert, J. (February, 1977). Building Standards and Codes for Energy Conservation. *Journal of Architectural Education*, v. 30, no. 3, p. 54-57.

Handlin, D.P. *(*2004). *American Architecture*. London: Thames & Hudson.

Hassel, S., Hannas, B., Blasnik, M. (2011). Energy-Efficient Homes: Predictions, Performance, and Real-World Results. *Home Energy, 28*, 28-33.

Heldenbrand, J. (January, 2001). A Century of Excellence in Measurements, Standards, and Technology: A Chronicle of Selected NBS/NIST Publications, 1901-2000. Lide, D.R., (Ed), *National Institute of Standards and Technology Special Publication 958*, 260-265. U.S. Government Printing Office, Washington, D.C.

Hills, R.L. (1989). *Power from steam: a history of the stationary steam engine.* Cambridge (UK): Cambridge University Press,.

Hubbert, M. (February, 1949). Energy from Fossil Fuels. *American Association For The Advancement of Science, 109*, 103-109.

ICASBS. (2009). Retrieved September 2011, from www.icasbs.com: http://www.icasbs.com/images/GuardedHot-BoxTesting.pdf

ICE HOUSE CONSTRUCTION. (July- December 1897). *Ice and refrigeration, v 13*, p 97-101.

Inglis, C. (2011). Thermal Mass. *Sustainable Living: Does It Measure Up?* Melbourne, Australia: Brickworks Building Products.

Jarnagin, R. (December, 2010). Energy profile: Where have we been, and where are we headed? Looking at energy consumption patterns of the past can help us promote responsible energy use in the future [Electronic Version]. *Consulting-Specifying Engineer*. Retrieved August 6th, 2011 from http://m.csemag.com/index.php?id=2832&tx_ttnews[tt_news]=40209&cHash=28f2450f4c

Kimball, F., Edgell, G.H. (1918). *A History of Architecture*. New York: Harper & Bros.

Krigger, J., Dorsi, C. (2009). *Residential Energy: Cost Savings and Comfort for Existing Building*. Montana: Saturn Resource Management, Inc.

Kostof, Spiro. (1985). *A History of Architecture: Settings and Rituals.* New York: Oxford University Press.

Karbuz, S. (May, 2007). US military energy consumption – facts and figures. Retrieved March 20th, 2011, from: http://www.energybulletin.net/node/29925

Kusuda, K. (2001). Building environment simulation before desk top computers in the USA through a personal memory. *Energy and Buildings, 33*, 291±302

Lamm, M. (2007, Spring). The Fiberglass Story [Electronic Version]. *Invention & Technology.* Retrieved on February 10th, 2010, from http://is.gd/a6veh

Libby, W. (1918). *An introduction to the History of Science*. London: Harrap.

Lienhard, J.H. *The Engines of Our Ingenuity, No. 1686: MYSTERIOUS HEAT*. Transcription retrieved July 8th, 2011 from http://www.uh.edu/engines/epi1686.htm

Lubliner, M., Blasnik, M., Kunkle, R., Gordon, A. (2009). Measured vs. Predicted Analysis of Energy Star Modular Permanent Military Housing: Fort Lewis Case Study. *Washington State University Extension Energy Program for USDOE*.

Lynn Benningfield, John Hogan. (2003). *Building Energy Code Enforcement: A Looke at California and Seattle.* Seattle: Heschong Mahone Group, City of Seattle.

Marschall, L.A., Mran, S.P. (2009). *Galileo's New Universe: The Revolution in Our Understanding of the Cosmos*. Dallas: Benbella Books, Inc.

McAlester, Virginia and Lee. (1994). *Great American Houses and Their Architectural Styles*. New York: Abbeville Press.

McChord Air Museum. (2011). *McChord Air Museum*. Retrieved April 2011, from McChord Air Museum, Our History: http://www.mcchordairmuseum.org/REV%20B%20TITLES%20OUR%20HISTORY4.htm

McMakin, A. H., Lundgren, R. E., Malone, E. L. (1999, October). Energy Efficiency Campaign for Residential Housing at the Fort Lewis Army Installation. *Pacific Northwest National Laboratory*, Technical Report PNNL-13089.

Min, J., Hausfather, Z., Lin, Q. F. (2010). A High-Resolution Statistical Model of Residential Energy End Use Characteristics for the United States. *Journal of Industrial Ecology,14*, 5, 791-807.

Minol. (2011). *Products and Services*. Retrieved January 25, 2011, from Minol USA: http://www.minolusa.com/products-services.html

NASA. (2010, September). *What is Thermodynamics?* Retrieved March 2011, from National Aeronautics and Space Admin: http://www.grc.nasa.gov/WWW/k-12/airplane/thermo.html

National Housing Research Committee/Concordia University. (2010, April). *Conceptualized Reference Database for Building Envelope Research*. Retrieved January 25th, 2011, from Conceptualized Reference Database for Building Envelope Research: http://users.encs.concordia.ca/~raojw/crd/

National Renewable Energy Laboratory. (2011). Building Energy Optimization (BEOPT). Golden, Colorado, US.

NIST. (2011, July 27th). *Early Guarded-Hot-Plate Apparatus*. Retrieved August 9th, 2011, from NIST Engineering Laboratory: http://www.nist.gov/el/building_environment/history.cfm

Northwest Power and Conservation Council. (2011). *Hydro-Thermal Power Program*. Retrieved August 2011, from Northwest Power and Conservation Council: http://www.nwcouncil.org

Office of the Deputy Under Secretary of Defense. (2011, May 17th). *Facilities Energy Directorate*. Retrieved March 11th, 2011, from Office of the Deputy Under Secretary of Defense: Installations and Environment: http://www.acq.osd.mil/ie/energy/index.shtml

Ostrander, C., Satko, J. (2011) History of Insulation with Masonry. *Masonry Advisory Council*. Retrieved July12th, 2011 from http://www.maconline.org/tech/rvalues/historyofinsulation/historyofinsulation.html

Palmiter, L., DeLaHunt, M. J.,Hanford, J. (1984). Optimal Conservation for 23 Northwest Climates. *Ecotope, Inc.*, Seattle, WA.

Parroco, C. (2011, May). *Influence of Design and Climate Change on the Annual Energy Consumption of a Passive Solar House*. Master's thesis. Washington State University, Pullman, WA.

Prasher, R., McCormick, C. (2010, March). Building Energy Efficiency, ARPA-E Pre-Summit Workshop.

Proctor, J., Downey, T., Blasnik, M. Diagnosing ducts: Finding the energy culprits. *Home Energy,10*, 26-31.

Rexroad APG, LPA. (July, 2010). *Comprehensive Energy and Water Master Plan: Joint Base Lewis-McChord.* United States Army Corps of Engineers Contract No: W912DY-06-D-0006-0018.

Ringsurf. (2009). *History of Asbestos*. Retrieved 2 21, 2010, from Ringsurf: http://www.ringsurf.com/online/2061-history_of_asbestos.html

Sherman, M. (1998, March). The Use of Blower-Door Data. *Lawrence Berkley National Laboratory*, Technical Report #35173.

Shirtliffe, C. J., Tye, R. P. (1985). Guarded hot plate and heat flow meter methodology: a symposium. *ASTM Committee C-16 on Thermal Insulation, National Research Council of Canada*.

Smil, V. (2006). *Energy: A Beginner's Guide*. Oxford: Oneworld.

Sommers, P. (July, 2004). Economic Impacts of the Military Bases in Washington, Ft. Lewis and McChord AFB in Pierce County. *Washington State Office of Financial Management*.

South Sound Military & Communities Partnership. (2012). *Final Plan*. Retrieved January 25th, 2011, from Joint Base Lewis-McChord Growth Coordination Plan: http://www.jblm-growth.com/plan.php

Spears, J. (1992). Residential Duct System Performance Evaluation Literature Review. *Electric Power Research Institute,* Technical Report-101347.

Swan, L. G., Ugursal, V. I. (September, 2008). Modeling of end-use consumption in the residential sector: A review of modeling techniques. *Renewable and Sustainable Energy Reviews,* 13, 8, 1819-1835.

Steucke, P. *Joint Base Lewis McChord Sustainability Program.* Environmental Division – Public Works, JBLM, Washington. GreenGov Symposium 2, Washington D.C. October, 2010.

Tacoma Power. (2011). *Tacoma Power*. Retrieved December 2011, from Tacoma Power: http://www.mytpu.org/tacomapower/conserve-energy/conserve-at/weatherization/Default.htm

Texas Alliance of Energy Producers. (2012). *The many uses of petroleum.* Retrieved February 26th, 2011, from Texas Alliance of Energy Producers: http://www.texasalliance.org/admin/assets/PDFs/The_many_uses_of_Petroleum.pdf

The Exchange. (2011). *The Exchange*. Retrieved February 16th, 2011, from The Exchange: http://www.shopmyexchange.com/

U.S. Army. (n.d.). *Fort Lewis History* . Retrieved February 28th, 2011, from Lewis Army Museum: http://www.lewis.army.mil/dptms/museum/history.htm

U.S. Army. (2011, December). *Joint Base Lewis-McChord*. Retrieved July, 2011, from Joint Base Lewis-McChord: http://www.lewis.army.mil/

U.S. Department of Defense. (2012). *BRAC Base Realignment and Closure 2005*. Retrieved 2011, from U.S. Department of Defense: http://www.defense.gov/brac/

U.S. Department of Energy. (2001, October 16). Energy Star Home Sealing Specification. United States.

U.S. Department of Energy. (2011, February). *Energy Savers*. Retrieved May 2011, from U.S. DOE, Energy Efficiency & Renewable Energy: http://www.energysavers.gov/your_home/insulation_airsealing/index.cfm?mytopic=11510

U.S. Department of Energy. (2012). *Energy Sources*. Retrieved 2011, from ENERGY.GOV: http://energy.gov/science-innovation/energy-sources

U.S. Department of Energy: Energy Efficiency & Renewable Energy. (2011, April). *Tax Credits for Energy Efficiency*. Retrieved December 2011, from Energy Savers: http://www.energysavers.gov/financial/70010.html#products_2011

U.S. Department of Energy. (2011). *Fuel Economy: Where the Energy Goes*. Retrieved December 27th, 2011, from www.fueleconomy.goc: http://www.fueleconomy.gov/feg/atv.shtml

U.S. DOE, Energy Efficiency & Renewable Energy. (2011, April). *Tax Credits for Energy Efficiency*. Retrieved December, 2011, from Energy Savers: http://www.energysavers.gov/financial/70010.html#products_2011

U.S. Energy Information Asministration. (2012). *Independent Statistics & Analysis*. Retrieved 2011, 2010, from Independent Statistics & Analysis: http://www.eia.gov/

United States Army. (n.d.). *Fort Lewis History* . Retrieved February 28th, 2011, from Lewis Army Museum: http://www.lewis.army.mil/dptms/museum/history.htm

U.S. Department of Defense. (2005). Letter to Requirements and Billing Info to Fort Lewis Residents Regarding Army's Residential Communities (RCI) Residential Utility Policy.

U.S. Department of Defense. (2008). Memo and Attachment: Army's Residential Communities (RCI) Residential Utility Policy Update.

Valleriani, M. (2010). *Galileo Engineer*. New York: Springer.

Walker, I.S., Sherman, M. H. (2008). Energy implications of meeting ASHRAE Standard 62.2. *Lawrence Berkley National Laboratory*, Technical Report-62446.

Washington State Department of Commerce. (2009). *Washington State Energy Office*. Retrieved May 7th, 2011, from WA Department of Commerce: http://www.commerce.wa.gov/site/526/default.aspx

Wyllie-Echeverria, S., Cox, P., (October-December, 1999). The Seagrass (Zostera Marina [Zosteraceae]) Industry of Nova Scotia (1907-1960). *Economic Botany*, 53, 4, pp. 419-426.

Zarr, R. (June, 2001). A History of Testing Heat Insulators at the National Institute of Standards and Technology. *ASHRAE Transactions*, *107*, Pt. 2.

Zogg, R. A., Alberino, D. L. (1998). Electricity Consumption by Small End Uses In Residential Buildings, Final Report. Arthur D. Little, Inc. Cambridge, MA.