SELECTING ENERGY EFFICIENT BUILDING ENVELOPE RETROFITS TO EXISITING DEPARTMENT OF DEFENSE BUILDINGS USING VALUE FOCUSED THINKING

THESIS

David M. Pratt, Captain, USAF

AFIT/GEM/ENV/06M-14

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

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David M. Pratt, BS

Captain, USAF

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David M. Pratt, BS
Captain, USAF

Approved:

//signed//

____ _____________

Lt Col Ellen C. England (Chairman) date

//signed//

____ _____________

Lt Col Jeffery D. Weir (Member) date

//signed//

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Charles A. Bleckmann (Member) date

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Abstract

The Department of Defense (DoD) has hundreds of thousands of facilities in its inventory, which consume billions of BTUSs of energy per year. Much of that energy is used to heat and cool the facility, and a great deal of this energy is lost through the building envelope. While new military construction works towards energy efficiency, the majority of DoD facilities were built over forty years ago with little regard to energy efficiency, and it is these facilities that have the greatest potential for energy efficient building envelope retrofits.

There are hundreds of various new building envelope technologies available to retrofit an existing building envelope, including window, roof, and wall technologies. This research investigated fifteen different building envelope technologies and found that many of them are feasible alternatives for DoD facilities. Value Focused Thinking (VFT) was the methodology used to objectively compare these new technologies and capture what Air Force decision makers value in regards to retrofitting older facilities with these new building envelope technologies. Data from three different Air Force bases and values from three different Air Force Civil Engineer Operations Flight Chiefs were used to evaluate these fifteen technologies, and the results show that the energy efficient window technologies have the highest potential for energy savings at each location. However, the research also shows that each of these technologies is a viable option and should always be considered when retrofitting an existing facility.

To my beautiful wife and daughter

Acknowledgments

I would like to express my sincere appreciation to my faculty advisor, Lt Col Ellen England for all of her help and insight throughout this entire process. Without her inspiration I would never have decided pick a research topic in the realm of sustainable design. I would also like to thank Lt Col Jeffery Weir for his help with the decision analysis portion of this research and Dr. Charles Bleckmann for reviewing my thesis drafts.

Special thanks to Mr. Tim Adams at AFCESA for his dedication to making this research a useful tool for the Air Force, as well as Mr. Larry Spangler for his insights concerning existing Air Force facilities. Additionally, I would like to thank each of the decision makers who provided their inputs on this research. I learned a great deal from each of them concerning the difficulty of maintaining Air Force facilities and what is really important when it comes to energy efficient projects.

I would also like to thank Mr. Marlin Addison for his help in using the EQuest energy simulation software, and all of the manufacturers and contractors that provided details on these new building envelope technologies.

Lastly I would like to thank my family, particularly my wife for all of her love and support throughout my time spent here at AFIT. Without her this research would never have been accomplished.

David M. Pratt

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SELECTING ENERGY EFFICIENT BUILDING ENVELOPE RETROFITS TO EXISITING DEPARTMENT OF DEFENSE BUILDINGS USING VALUE FOCUSED THINKING

I. Introduction

1.1 Background

The Federal Government maintains more than 500,000 facilities in the United States and around the world (Clinton, 1999), most of which are heavily dependant on fossil fuels to produce electricity. In fiscal year (FY) 2002, federal facilities used 316.8 trillion British Thermal Units (BTUSs) of energy at a cost of $3.7 billion, making the Federal Government the single largest energy consumer in the United States (Garman, 2004). Through Executive Order (EO) 13123, “Greening the Government through Efficient Energy Management,” President Clinton ordered that the Federal Government significantly improve its Energy Management in order to save taxpayer dollars and reduce emissions that contribute to air pollution and global climate change (Clinton, 1999). Energy Management is defined by Turner (2001) as the regulation of energy consuming devices for minimizing energy demand and consumption. It is an important tool to help the Federal Government meet not only those economic and environmental objectives mandated in EO 13123, but meet its energy demands and promote energy conservation in environmentally responsible ways that set a standard for the world (Bush, 2001).

Energy Management can help improve environmental quality by reducing fossil fuel consumption, thus reducing emissions into the atmosphere of such substances as nitrogen oxides, sulfur oxides and carbon dioxide, which have been suggested to affect

Global Warming as well as produce acid rain (Energy Information Administration, 2005). For many years, researchers have been developing alternative technologies to fossil fuels to produce electricity such as solar panels, wind turbines, and geothermal plants to help reduce the amount of fossil fuel we use and lessen the United States's dependence on oil. Effective energy management can reduce the total amount of energy used, whether a facility uses fossil or alternative fuel, which is not only better for the environment but also could save the federal government millions of dollars each year.

The United States was self sufficient in energy until the early 1950s. However, by the 1970s, America was importing almost 35% of its energy needs and U.S. petroleum reserves were nearly exhausted (Trumbore, 2002). The United States did not appear to be concerned with its energy situation until the Organization of Petroleum Exporting Countries (OPEC) oil embargo of 1973-74. In response to this crisis, the federal government took steps to conserve energy such as extending Daylight Savings Time and imposing a federal speed limit of 55 mph (Wikipedia, 2005). Also stemming from the oil crisis was the development of the Department of Energy (DOE) in 1977 and the Trans-Alaskan Oil Pipeline, also completed in 1977 (Wikipedia, 2005).

Following the oil embargo, the U.S. established its first energy guidelines. President James E. Carter created America's first energy policy. He stated that the U.S. must balance its demand for energy with the world's rapidly shrinking resources, and conservation is the quickest, cheapest, most practical source of energy (Carter, 1977).

President George H.W. Bush signed the Energy Policy Act (EPAct) of 1992 into law on October 24, 1992 (Bush, 1992). Subtitle F of the EPAct ordered federal agencies to reduce their energy consumption per square foot of building, install energy conservation features, track energy consumption, and institute systems to facilitate the funding of energy efficiency improvements (Bush, 1992)**.**

On June 3, 1999, President William J. Clinton signed EO 13123. EO 13123 increased and extended energy efficiency goals by requiring each agency to reduce building energy consumption per square foot by 30 percent by 2005 and 35 percent by 2010, relative to a 1985 baseline (Clinton, 1999). In particular, this federal policy calls on agencies to minimize energy and resource consumption, enhance indoor environmental quality and optimize operational and maintenance practices (Clinton, 1999).

Even with these energy policies in place, the United States continues to consume more energy than it produces, furthering the dependence on foreign countries for its energy needs. In 2004, the United States consumed approximately 100 Quadrillion British Thermal Units (Quad BTUSs) of Energy while only producing about 75 Quad BTUSs. America's consumption of energy is projected to increase to over 125 Quad BTUSs by the year 2020 while its production is expected to remain relatively constant. This rift between our energy consumption and production will only increase if measures are not taken to reduce the United States's energy usage as shown in Figure 1.1.

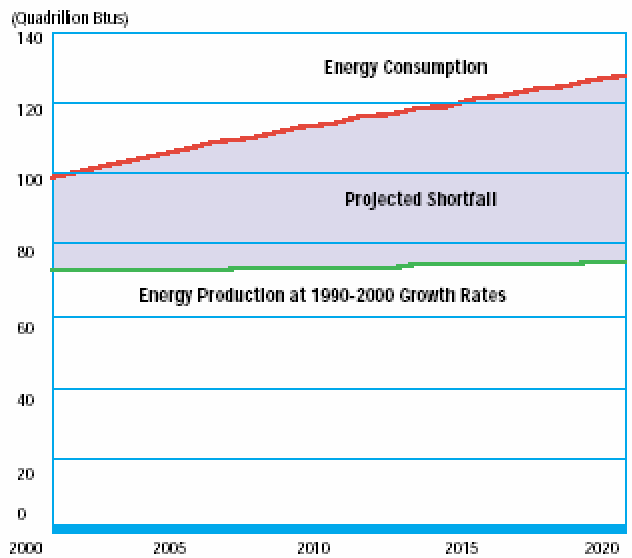

Figure 1.1: U.S. Energy Consumption. Over the next 20 years, growth in U.S. energy consumption will increasingly outpace U.S. energy production if production only grows at the rate of the last 10 years (Bush, 2001)

From these policies, it is apparent that the federal government has recently been attempting to reduce the gap between energy consumption and production by promoting energy efficiency. One of the ways to improve energy efficiency is to improve the building envelope by applying new technologies. These technologies include but are not limited to the following: low-emissivity (low-e) windows that allow less heat through to the indoor environment, insulating concrete forms to insulate the foundation or basement slab from the ground, advanced wall-framing techniques that are more energy efficient or Structural Insulating Panels (SIPs) that can be used as highly insulated walls or ceilings, and cool roofing that can reflect the heat off a building. Technologies that promote energy efficiency can also be as simple as improved landscaping to provide shading or block prevailing winds (DOE, 2005b).

1.2 Problem Statement

DoD currently has guidelines for new construction pertaining to the energy efficiency of the building envelope. The Code of Federal Regulations (CFR) Title 10 states that the desired goal of the energy design of the building envelope shall be to produce a controlled membrane that allows or prevents heat, light, and moisture flow to achieve a balance between internal and external loads (CFR, 2000a), while the United Facilities Code (UFC) states that sustainable design shall be an integral part of every project and energy conservation is a primary goal of sustainable design (UFC, 2002)

Unfortunately, these guidelines only pertain to the construction of new facilities. These new facilities are only a small percentage of the numerous DoD buildings. The potential energy savings by renovating or retrofitting existing DoD buildings with these new energy efficient technologies remains virtually untapped. By using Energy Savings Performance Contracts (ESPCs) and Utility Energy Savings Contracts (UESCs) to retrofit existing DoD buildings, the federal government could likely save millions of dollars each year. The savings alone could likely pay for the construction of the new technologies within a matter of years and provide an opportunity for the federal government to lead by example (DOE, 2005d).

Currently there are no guidelines for these types of renovations and retrofits to existing DoD buildings. Military leadership, engineers, and energy managers have no way to compare the different building envelope technologies against each other to see which technology might work best for a given facility. Therefore, the purpose of this research is to develop a model that measures the value of these different building envelope technologies, capturing federal energy objectives as well as military leadership's objectives, while at the same time maintaining building occupants' comfort. This model will be developed so it can be used at any DoD facility, regardless of environmental conditions.

1.3 Research Objective/Questions

The objective of this research was to provide decision makers with a multiple objective Value-Focused Thinking (VFT) model that can evaluate various building envelope technologies available for retrofit of a given DoD facility. This research attempted to answer the following questions:

1. What energy saving building envelope retrofit technologies are available for use and where have they been used successfully?
2. What do decision makers in the Department of Defense value in terms of building envelope performance and indoor air quality (IAQ)?
3. How much energy will be saved by incorporating these energy saving building envelope retrofit technologies?
4. What is the most appropriate policy vehicle to incorporate these technologies into existing buildings?

1.4 Research Approach

The purpose of this research was to create a model that will objectively evaluate the various energy saving building envelope technologies. To do this the decision maker had to determine what his or her values were for each attribute of the technology in question and weighted those attributes appropriately. Building envelope technology attributes may include total costs, energy saved, aesthetics, safety, maintenance and ease of installation. This process gave the decision maker insight as to what values are important to him or her in regards to these new building envelope technologies and which technology may be most useful in a particular situation as well as possibly develop new alternatives not previously thought of. To accomplish this, Value Focused Thinking (VFT) was employed. Specifically, VFT was used to answer research question two by suggesting how a decision maker should think systematically about identifying and structuring objectives, about making vexing value tradeoffs, and about balancing various risks (Keeny, Raiffa 1993). Research questions one and four were answered using a search of the current literature. Research question three was answered by using energy simulation software that will simulate the energy use of a typical DoD facility as defined by the Air Force Civil Engineer Support Agency (AFCESA), and then this "saved energy" was incorporated into the VFT model.

1.5 Scope

This research was limited by several factors. First, the value of any building envelope technology acquired from the decision maker is subjective, because it will be obtained by questioning key decision makers in DoD on what they deem important when incorporating these technologies into current DoD facilities. These decision makers include experts at AFCESA as well as energy managers and Civil Engineers at various Air Force locations. Therefore, the results of the VFT model are limited to the opinions of the decision maker, and the model can produce various results by using different decision makers. Secondly, the "energy saved" by incorporating these technologies was simulated using a reputable computer program (EQuest). To definitively state how much energy can be saved, the actual performance would have to be compared with prior performance after retrofit construction was complete and the building was monitored for energy performance. However, with these limitations it's likely that this research will shed new light on what the federal government can do to conserve energy and this model will be applicable to any DoD installation.

1.6 Significance:

The significance of this research was the creation of a model that can be used at any DoD facility to assist decision makers on how to retrofit existing buildings to make them more energy efficient. The model also illustrates what is important to the decision makers in terms of building envelope performance, and the use of the model may lead to alternatives not previously thought of. By employing this model, military leaders should be able to make the best decision to retrofit an existing building with new building envelope technologies.

1.7 Summary:

In his recent National Energy Policy, President George W. Bush states that a fundamental imbalance between supply and demand defines our nation's energy crisis, and this imbalance, if allowed to continue, will inevitably undermine our economy, our standard of living, and our national security (Bush, 2001). If the U.S. continues to consume more energy than it produces, it will continually be dependant on foreign sources of energy to meet its needs. While there are many schools of thought on producing more energy to meet those goals, it seems that we could meet the same goals by simply using less energy. Conserving energy would be not only more economical but it would lead the way in environmental excellence. In order to become energy independent, the U.S. must lead the way in Energy Management and, hopefully, this research will be a step in that direction.

II. Literature Review

2.1 Overview

This chapter introduces the basic theory of heat transfer and summarizes the basic characteristics of a building envelope. The common energy losses that building envelopes suffer and new energy saving technology that can be retrofitted into an existing building to minimize these energy losses are introduced and detailed. Furthermore, this chapter explores the considerations a decision maker must face when retrofitting an existing building envelope. Finally, the theory of decision analysis and the advantages and disadvantages of various decision-making methodologies are discussed.

2.2 Heat Transfer Background

Heat transfer is energy in transit due to a temperature difference. Whenever there exists a temperature differential in a medium or between media, heat transfer must occur (Incropera and Dewitt, 1996). There are three different modes of heat transfer known as conduction, convection and radiation. Conduction is the heat transfer that occurs across a medium due to a temperature differential. Convection is the heat transfer that occurs between a surface and a moving fluid when the two have different temperatures, and radiation is a form of energy in electromagnetic waves and occurs in the absence of a medium (Incropera and Dewitt, 1996). The building envelope is a medium in which heat transfer occurs when there is a temperature difference between the inside of the building and the outside environment. Most heat transfer problems involve more than one mode of heat transfer (Mills, 1999). An example of this would be the heat loss of a warm building to the cool outside air through a roof. Heat is transferred to the ceiling by convection of the warm room air and by radiation from the walls, furniture and occupants. The heat is then transferred through the ceiling and insulation by conduction, across the attic crawlspace via convection and radiation, and out the roof tiles by conduction. Finally the heat is transferred to the cold ambient air by convection and radiation (Mills, 1999).

In order to have a realistic equation to model heat transfer, such as that just described for the building, each of these modes of heat transfer must be taken into account. However, the focus of this research is on different conductive and radiative building envelope technologies; the analysis assumes the various convective heat transfers that occur at the surface of a building envelope will not change when different building envelope technologies are introduced. The only exception is the convective heat transfer benefit of from landscaping, discussed in section 2.4.5.

Conductive heat transfer can be quantified using Fourier's Law. Fourier's law states that the heat flux (*q*), the heat transfer per unit area, is governed by the following rate equation (Incropera and Dewitt, 1996):

$$q = -k\frac{dT}{dx} \qquad \text{Eq 2.1}$$

Where:

q is the heat transfer per unit area per time $\left(\frac{Btu}{(hr)(ft^2)}\right)$

$\frac{dT}{dx}$ is the temperature gradient $\left(\frac{°F}{ft}\right)$

k is the thermal conductivity of the medium $\left(\frac{Btu}{(hr)(ft)(°F)}\right)$

The conductive heat transfer rate $\dot{Q}_{cond}$ is the heat flux multiplied by the area of the medium. Simplifying Equation 2.1 after integrating the temperature gradient (assuming the gradient is linear under steady state conditions) and multiplying by the area gives an easier rate equation to use (Mills, 1999):

$$\dot{Q}_{cond} = kA\frac{T_1 - T_2}{L} = kA\frac{\Delta T}{L} = \frac{A\Delta T}{L/k} = \frac{A\Delta T}{R} = U_O A\Delta T \qquad \text{Eq 2.2}$$

Where:

$\dot{Q}_{cond}$ = conductive heat transfer rate $\left(\frac{Btu}{(hr)}\right)$

T_1 = exterior temperature of material (°F)

T_2 = interior temperature of material (°F)

L = thickness of material (*ft*)

A = cross sectional area of material (ft^2)

k = thermal conductivity of material $\left(\frac{Btu}{(hr)(ft)(°F)}\right)$

R = thermal resistance, R-value $\left(\frac{(hr)(ft^2)(°F)}{Btu}\right)$

U_O = overall heat transfer coefficient $\left(\frac{Btu}{(hr)(ft^2)(°F)}\right)$

ΔT = temperature difference between exterior and interior surfaces of material (T_1 - T_2, °F)

The thermal conductivity and thickness of the material determines at what rate energy is transferred by conduction through the medium. *L/k* can be viewed as the thermal resistance (*R*) of the medium. This thermal resistance is also known as the R-value of the medium. The higher the R-value of a material, such as insulation, the slower the heat flows through (Mills, 1999). If the medium is a composite of more than one material (as are most parts of the building envelope), the overall heat transfer rate through the composite is (Mills, 1999):

$$\dot{Q}_{cond} = A\frac{T_1 - T_2}{R_A} + A\frac{T_2 - T_3}{R_B} = A\frac{T_1 - T_3}{R_A + R_B} = \frac{A\Delta T}{R_A + R_B} \qquad \text{Eq 2.3}$$

Where:

$R_A = \frac{L_A}{k_A} \left(\frac{(hr)(ft^2)(°F)}{Btu}\right)$

$R_B = \frac{L_B}{k_B} \left(\frac{(hr)(ft^2)(°F)}{Btu}\right)$

An illustration of conductive heat transfer through a composite material is shown in Figure 2.1.

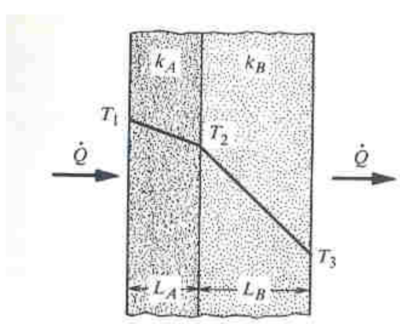

Figure 2.1. Conductive heat transfer through a composite material (Mills, 1999). Resistance to heat transfer differs in material A and material B

The overall heat transfer coefficient U_O is defined as the inverse of the combined thermal resistance of the composite material (Mills, 1999). In the case of Figure 2.1, the U-value would be 1/ (R_A + R_B). While R-values are given to materials such as insulation, U-values are typically used to describe the thermal conductivity of windows. As stated above, the higher the R-value of a material, the greater its insulating properties and the slower the heat flows through it. Therefore, the lower the U-value, the slower the heat flows through it.

The only radiative heat transfer this research is concerned with is solar radiation, that is, the heat that is transferred from the sun to the building. This type of heat transfer mostly occurs through translucent window glazing, and is discussed in Section 2.4.2. Solar radiation also occurs at the roof, walls and doors, and the effect of solar radiation on these parts of the building envelope are discussed in the upcoming sections.

2.3 Building Envelope Background

A building envelope generally refers to the building components that enclose conditioned spaces and through which heat energy is transferred to or from the outdoor environment (Turner and Elder, 2001). This heat transfer is called heat loss when the indoor temperature being maintained is greater than the outdoor temperature, usually in the winter. The heat transfer that occurs when the indoor temperature being maintained is less than the outdoor temperature is called heat gain. Heat gains or heat losses translate into increased energy use to condition the interior space. Figure 2.2 shows a superimposed plot of average monthly temperature and energy consumption for a natural gas heated facility in the Northwest region of the United States. Figure 2.2 shows that the lower the average monthly temperature, the more energy is consumed to heat the facility (Turner and Elder, 2001).

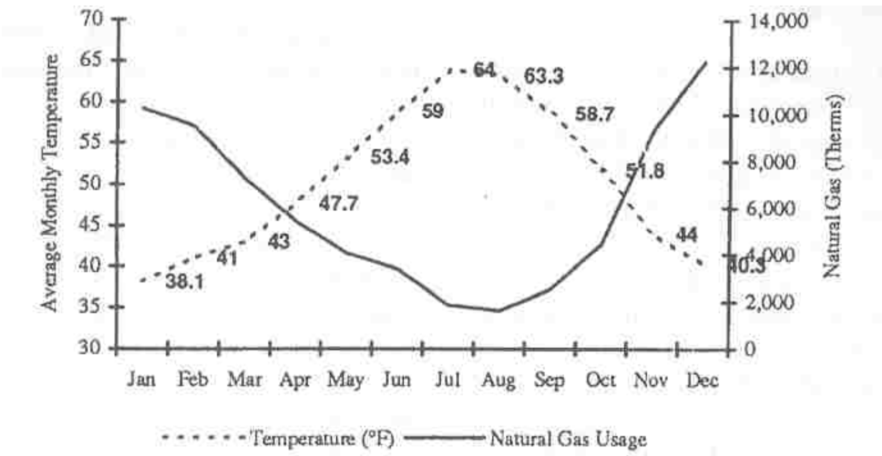

Figure 2.2. Natural gas usage versus monthly temperature. As the average monthly temperature decreases, more energy is used to heat this facility in the Pacific Northwest (Turner and Elder, 2001).

More energy is needed to keep a constant temperature in the building because the heat energy is being transferred through the various components of the building envelope. Most of this energy (fifty percent) is transferred through the windows, as shown in Figure 2.3. 21% of the energy is transferred through infiltration, or air leakage in the building envelope. The remaining heat energy is transferred through the roof (16%); walls (10%); and floor or foundation (3%).

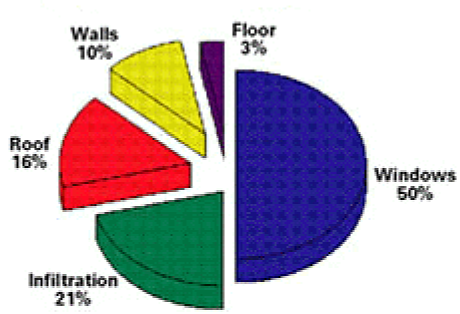

Figure 2.3: Building envelope energy losses of facilities 15 years or older (Elder, 2000). The majority of energy transfer occurs through the windows.

Equation 2.2 indicates there are two ways to lower the heat transfer rate through the building envelope. The first is to raise the thermal resistance, or R-value, in the building envelope components, possibly by increasing the length (or depth) of insulation or choosing insulation with a lower thermal conductivity *k*. The second is to lower the temperature difference between the indoor and outdoor environment, a more difficult challenge to overcome if occupant comfort is considered. For example, thermostats could be set to a higher temperature in the summer and lower in the winter. Also, building materials might be chosen to lower the temperature difference. Lowering the heat transfer rate of the building envelope will allow the mechanical systems to use less energy when heating and cooling the building, thus making the building more energy efficient. New and existing technologies are available to make a building more energy efficient.

2.4 Building Envelope Components

2.4.1 Roofs

The commercial industry uses a wide variety of roof types on its buildings, including but not limited to flat or low sloped, pitched, shingle, modified bitumen, single or multiple ply, and metal. A typical Air Force facility has a low slope built-up roof (BUR), usually 4-ply with 3 inches of polyisocyanurate insulation. The most common deck material is steel and the BURs are usually ballasted with stone (AFCESA, 2005a).

As mentioned in section 2.3, the two strategies to minimize conductive heat transfer are to either increase the R-value of the medium or lower the temperature difference between the exterior and interior environments. Roofs tend to be large "heat islands," where they absorb a large amount of radiant energy from the sun, causing the temperature of the roof, as well as the surrounding air, to rise. In fact, the surface temperature of a typical black asphalt shingle roof can be as high as 170 °F in the summer in a warm sunny climate (LBNL, 2000), even though the air temperature is approximately 90 °F. Therefore, if the interior space were maintained at a temperature of 80 °F, the temperature difference would be 90 °F. Much of the energy being transferred through the roof might be minimized if the temperature on the surface of the roof could be significantly lowered, perhaps by using a "cool roof" product. The Lawrence Berkley National Laboratory Heat Island Group has monitored buildings in Sacramento with lightly colored, more reflective roofs. They found that these buildings used up to 40% less energy for cooling than buildings with darker roofs (LBNL, 2000). The Florida Solar Energy Center performed a similar study, also showing up to 40% cooling energy savings (Parker et al, 1995).

The main purpose of a cool roof is to reflect the sun's radiant energy before it penetrates the interior of the building, thus reducing the amount of air conditioning needed to cool a facility (LBNL, 2000). A cool roof system is one that reflects solar radiation and also emits thermal radiation well (Akbari and Bretz, 1998). Solar reflectance, or albedo, is the fraction of solar radiation reflected by a surface. Materials with high solar reflectance values absorb less of the sun's energy and therefore stay cooler, reducing daytime air conditioning requirements (FEMP, 2004b). A cool roof can include any kind of reflective roof surface including lightly colored asphalt shingles, lightly colored ceramic tiles, or white acrylic roof coatings containing materials such as titanium oxide. Figure 2.4 shows the technologies having a higher solar reflectance have a lower temperature difference between the roof and the air.

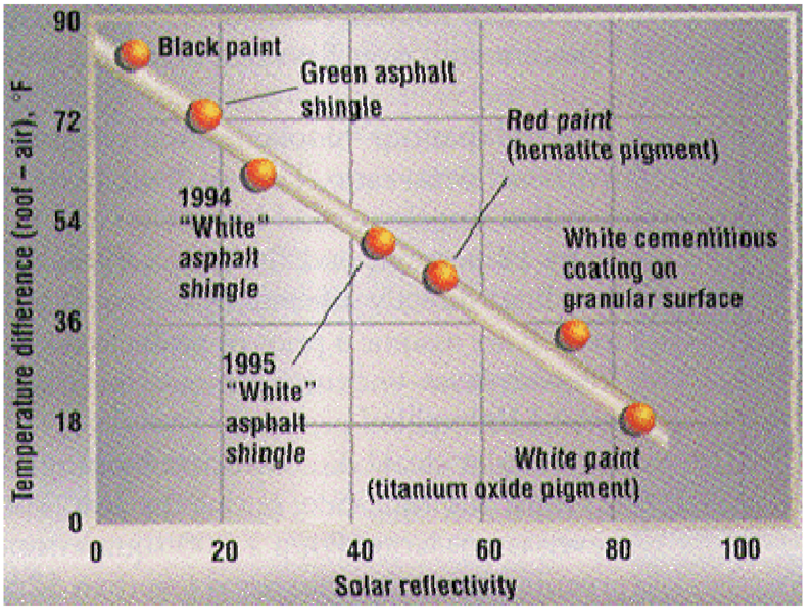

Figure 2.4. Solar reflectivity and temperature difference (LBNL, 2000). Technologies that have a higher solar reflectance have a lower temperature difference between the roof and air.

Another property of a cool roof is the material's emittance. Emittance is the amount of absorbed heat that is radiated from a roof. A higher emittance allows the roof material to release the heat it absorbs more quickly. A material with high solar reflectivity but a low emmitance (such as unpainted metal) causes the heat to be retained on the surface and ultimately transferred into the building (Akbari and Bretz, 1998).

The combined value of solar reflectance and emittance is known as the Solar Reflectance Index (SRI). SRI is the roof's ability to reject solar heat. It is defined so that a standard black asphalt shingle has an SRI of zero (reflectance 0.05, emittance 0.90) and a white shingle has an SRI of 100 (reflectance 0.80, emmitance 0.90) (LBNL, 2000). A roof with high reflectance but low emmitance such as unpainted metal will have a low SRI under 50 (LBNL, 2000).

Because cool roofs reflect the sun's radiant heat in the winter as well as the summer, they have the possibility of causing more energy use for heating a facility, but this is often offset by the energy savings in the summer (Akbari and Bretz, 1998). The Lawrence Berkley National Laboratory Heat Island Group modeled energy use in buildings with cool roof technology in eleven metropolitan areas using a computer simulation and projected the energy savings taking into account the "penalty" of additional energy needed to heat the building in the winter. The projection of annual net energy savings in 1998 dollars is shown in Figure 2.5. Energy savings projections in these cities alone range from 3 to 37 million dollars and totals 194 million dollars (Akbari and Bretz, 1998).

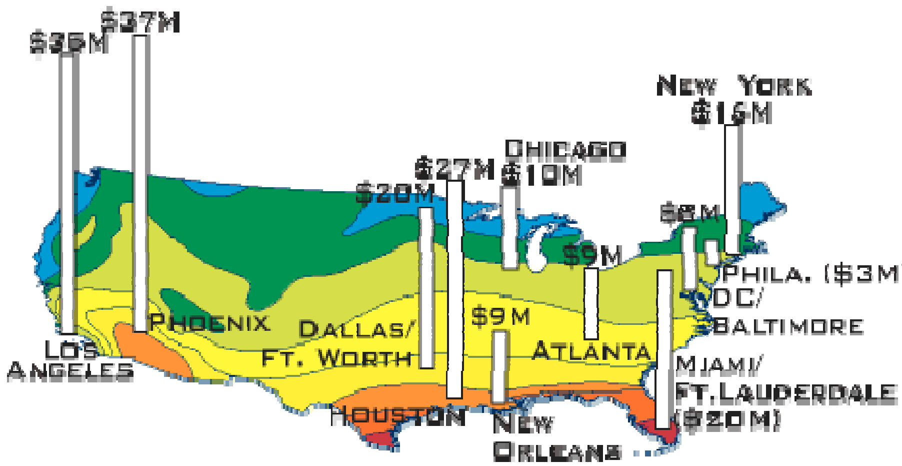

Figure 2.5: Annual Net Energy Savings in 1998 dollars in 11 metropolitan areas using cool roofs (Akbari and Bretz, 1998). Energy savings total 194 million dollars.

Green roofs are simply vegetated roof covers constructed atop and across a roof deck. Like cool roofs, green roofs can reduce the surface temperature of the roof as well as the surrounding ambient air temperature, thus combating the urban heat island effect (Velazquez, 2005). The absorbed radiation of a typical black asphalt roof not only raises the exterior temperature of the roof; it also raises the temperature of the surrounding air in densely populated urban areas. This also occurs with other impervious surfaces such as pavements. This higher ambient temperature acts as a catalyst and adds to smog, making air pollution problems worse as well. This is known as the urban heat island effect (FEMP, 2004b). While the concept of a green roof has been used since the 10th century B.C., the modern green roof was introduced in Germany in the 1970s and the technology became more widely accepted in Europe throughout the 1980s (Velazquez, 2005). There are two types of green roofs, extensive and intensive. Extensive green roofs typically have lower growing plants than intensive green roofs, and also have less variety or species. Intensive green roofs are usually designed for human recreation (as in a rooftop garden), while extensive are typically non-accessible. Extensive green roofs are also less expensive to install and maintain than intensive green roofs (Velazquez, 2005). However, both types of green roofs are built in the same fashion. The vegetation is planted in a type of growth medium with a drainage layer beneath it. Beneath the drainage layer is a root barrier and waterproof membrane, all constructed atop the insulated roof deck. Figure 2.6 shows a cross section of what a typical green roof would look like.

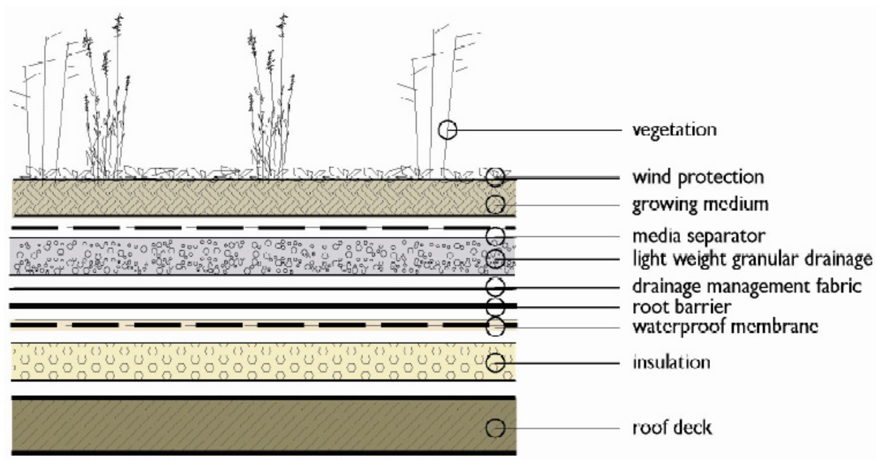

Figure 2.6: Cross section of a green roof (Dvorak and de la Fleur, 2005). Green roofs or not all alike but typically have the common components of waterproofing, drainage, a growing medium and plants.

As a contrast to cool roofs, green roofs not only have lower surface temperatures than conventional roofs, they also insulate more than conventional roofs, keeping more of the heat inside the facility during the winter and lowering the energy demand not only in the summer but also in winter (FEMP, 2004b). Green roofs also have additional environmental benefits such as reduction of stormwater as well as water quality and air quality improvement (Velazquez, 2005). The National Research Council of Canada conducted a field study on a test facility in Ottawa to evaluate the thermal performance of green roof technology over a two year period from 2000-2002. The reference roof was a bituminous roof with light gray gravel. The study found that the surface temperature of the green roof was significantly lower than that of the reference roof throughout the monitoring period. These lower surface temperatures in turn considerably reduced the heat flow through the green roof as compared to the reference roof during the summer months, lowering the space conditioning energy demand by 75%. The green roof also acted as an effective insulation during the winter months, reducing heat loss by 26% as compared to the reference roof (FEMP, 2004a). Figure 2.7 shows these results.

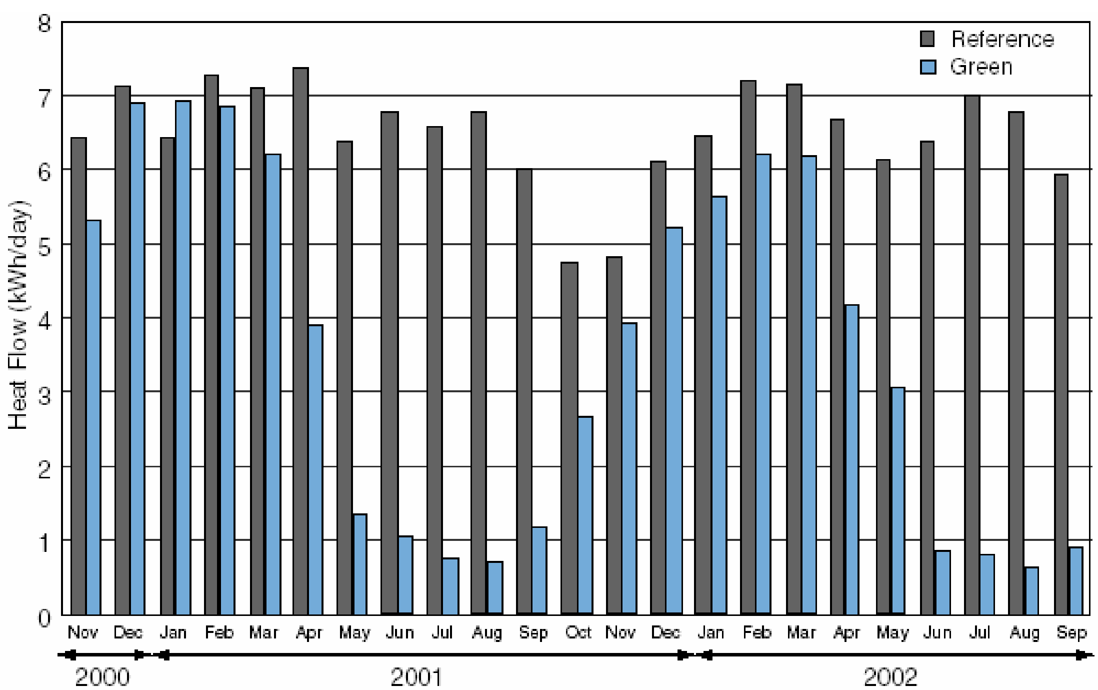

Figure 2.7: Average Daily Heat Flow through conventional and green roof systems (FEMP, 2004a). Measurements of heat flow show that the average daily energy demand was less in every month and significantly less during the summer months.

Weston Solutions Inc. conducted an energy study for the city of Chicago in December 2000. The study showed if the city greened all of its rooftops, peak electricity demand could be reduced by 720 megawatts, saving up to $100,000,000 annually. The change to green roofs could result in an average of 50% energy savings for cooling and 25% energy savings for heating (Velazquez, 2005). In fact, Chicago adopted an energy conservation ordinance in 2002 requiring all new and refurbished roofs to install green roofs or cool roofs. Tokyo adopted a similar measure in 2001 requiring new buildings larger than 10,000 square feet to green at least 20% of the building's usable roof space (Velazquez, 2005).

2.4.2 Fenestration (Windows/Doors)

Fenestration refers to the design and position of windows, doors, and other structural openings in a building (Elder, 2000). A window is actually a system of several components (Turner and Elder, 2001). Glazing is the transparent component of glass or plastic windows. The sash is the frame in which the glass panes of a window are set, and the frame is the complete structural enclosure of the glazing and sash system. Figure 2.8 shows these window components in detail.

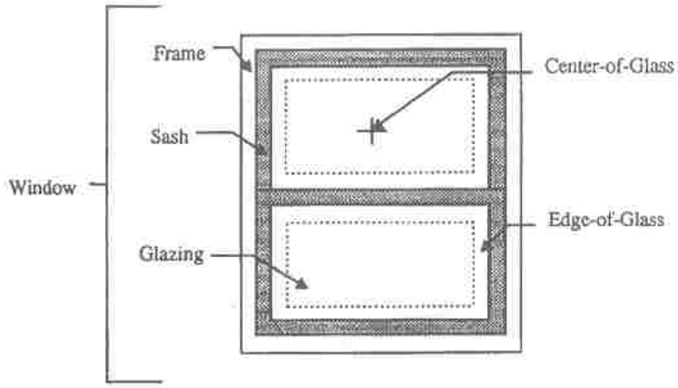

Figure 2.8: Detailed view of window components (Turner and Elder, 2001). A window is a system comprised of several components.

Fenestration affects building energy use through four mechanisms. These are conductive heat transfer, solar heat gain, air leakage, and daylighting (ASHRAE, 1997). Conductive heat transfer was defined in section 2.2. Solar heat gain is radiant heat from the sun that penetrates a building envelope through glazing that contributes to the heat load in a building. The Solar Heat Gain Coefficient (SHGC) is the fraction of solar energy that enters the window and becomes heat (DOE, 2005b). Air leakage is an uncontrolled flow of air through a component in the building envelope, and daylighting is the natural lighting provided by the sun. Therefore, the energy impacts of fenestration can be minimized by the following four techniques (ASHRAE, 1997). The first is to use appropriate glazing technologies to minimize conductive heat transfer; the second appropriate glazing and shading strategies to control solar heat gain and minimize cooling requirements; the third low air leakage fenestration products and lastly, the use of daylighting to offset building lighting requirements. The strategy of daylighting is beyond the scope of this research, but is certainly a good topic for future research.

As mentioned above, heat is transferred through fenestration by more than simple conduction. There is also radiant heat transfer from the sun to the building. Therefore, the heat transfer rate equation for fenestration is as follows (ASHRAE, 1997):

$$\dot{Q} = U_O A(T_1 - T_2) + SHGC_O A E_T \qquad \text{Eq 2.4}$$

Where:

$\dot{Q}$ = Heat transfer rate $\left(\frac{Btu}{(hr)}\right)$

U_O = Overall heat transfer coefficient, U-value $\left(\frac{Btu}{(hr)(ft^2)(°F)}\right)$

A = Area of fenestration (ft^2)

T_1 = Exterior air temperature (°F)

T_2 = Interior air temperature (°F)

$SHGC_O$ = overall solar heat gain coefficient (*non-dimensional*)

E_T = incident total irradiance $\left(\frac{Btu}{(hr)(ft^2)}\right)$

Equation 2.4 indicates that to minimize energy use for cooling a building, the U-value of the window as well as the solar heat gain coefficient must be as low as possible. Glass itself is a fairly conductive material; therefore a single glass pane window can transfer quite a bit of heat energy (Elder, 2000). This is unfavorable not only during the summer when cooling loads are high, but also in the winter when heating loads are high. A sealed window assembly with a minimum of two window panes separated by an air gap is known as an insulated glass unit (IGU) (ASHRAE, 1997). The addition of a second pane of glass can reduce the U-value of the window by almost fifty percent. The second pane of glass and the air gap between the two panes doubles the width of the glass material (*L* in Equation 2.2). A third pane of glass would have a similar effect. If the air between the glass panes were replaced with an inert gas that has a lower thermal conductivity, such as argon or krypton, the U-value of the window would decrease even more.

Glass windows also have an emissivity value that can be reduced by adding special coatings to the glass panes. Emissivity is the ability of a surface to transfer thermal radiation. The lower the emissivity of a surface, the lower the heat transfer due to radiation (Elder, 2000). When these low emissivity coatings are applied to a glass pane, the resulting product is called a "low-e" window. From the perspective of equation 2.4, these low-e windows actually lower the solar heat gain coefficient while allowing the visible light to pass through. Low-e windows also prevent the loss of interior heat in cooler climates. Because of these properties, low-e windows are appropriate for residential and commercial buildings throughout the United States (FEMP, 1998)

There are two techniques for applying low-e coating to glass. The first is called sputter coating, or a soft coat. This process magnetically deposits silver to the glass inside a vacuum chamber, and the soft coated surface must be protected within an IGU. Figure 2.9 displays a typical IGU, where the soft coat is applied to surfaces #2 and #3.

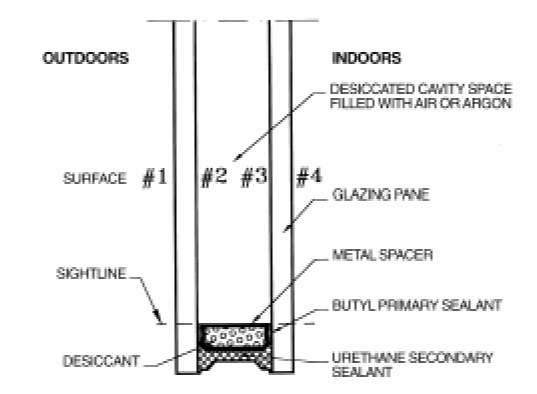

Figure 2.9: Typical IGU where soft low-e coatings are applied to glass surfaces #2 and #3 inside a vacuum (ASHRAE, 1997). Low-e windows allow solar light to pass through but reduce the amount of solar heat transfer.

The second process is called pyrolytic or hard coating. This method applies tin oxide to the glass while it is somewhat still molten, and can be used for single paned windows (Elder, 2000). While normal glass typically has an emissivity of about 0.84, hard coatings can have emissivities of 0.40 and soft coatings can have an emissivity of 0.10 or lower (Elder, 2001).

The window frame material also affects the overall thermal resistance. Metal frames such as aluminum and galvanized steel transfer heat more readily than wood or polymer frames such as fiberglass or vinyl. In fact, metal framing has such a negative impact on overall window performance, there is usually little benefit to incorporating other strategies, such as low-E films, argon gas, etc., unless the frame resistance is first improved (Elder, 2000). Figure 2.10 illustrates how these different glazing and frame technologies impact the overall thermal resistance (R-value) of the window.

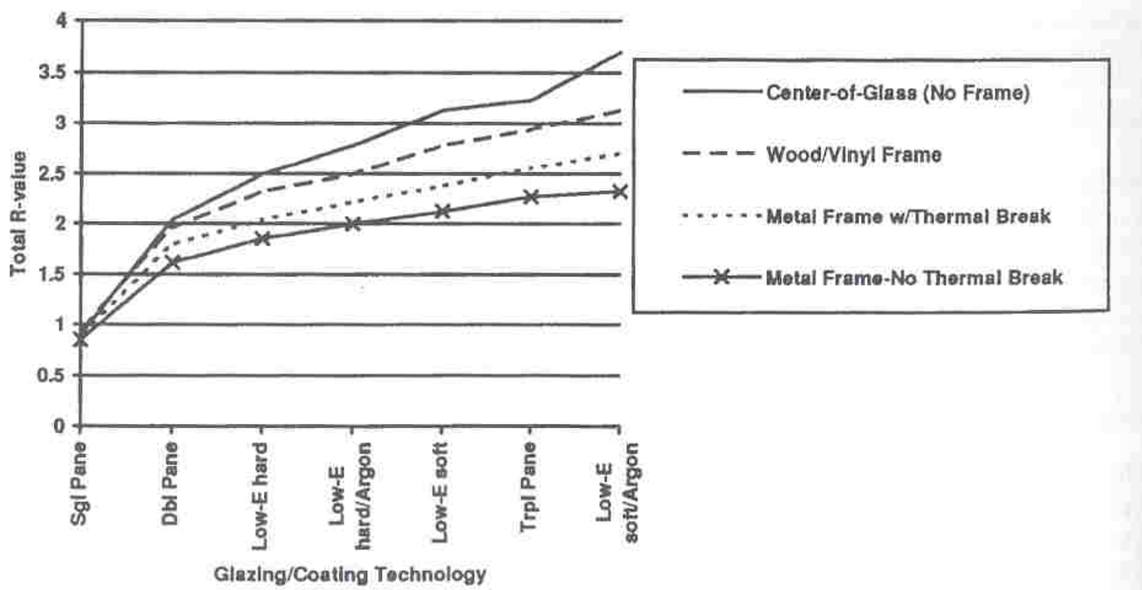

Figure 2.10: Impact to overall R-value of window from various glazing and frame technologies (Turner and Elder, 2001). The R-value of a window increases as multiple panes and less conductive gases are introduced.

These R-values are still small as compared to the R-value of a well-insulated wall or roof. That is why over 50% of all heat transfer in a building envelope occurs in the windows. However, research is currently under way at the Solar Research Institute to replace the air gap in a window with a vacuum, where a theoretical R-value of R-16 is possible (Elder, 2000).

Doors that are made of materials with low thermal resistances (such as metal) can simply be replaced with a door with a higher R-value (such as wood or a polymer) to minimize the heat transfer through the door. Door frames are similar to window frames in that they should also be made of a material with a high R-value in order to minimize conductive heat transfer. If the door has any glazing involved, then the same technologies available for windows can be applied to minimize conductive and radiative heat transfer.

There are still quite a large number of single paned windows in Air Force facilities, but the standard windows that are being installed are double paned with an aluminum frame with a thermal break (AFCESA, 2005a). In some new construction it is not unusual to see high performance reflective coatings specified.

2.4.2 Walls

The majority of Air Force facilities have masonry exterior with 1" air space and rigid board insulation on steel studs. There may even be some batt insulation between the studs (AFCESA, 2005a).

Most walls are a composite of an exterior face material, insulation, wood or steel studs, and an interior face material. Therefore the R-value of a typical wall is not usually uniform. In order to calculate the heat transfer through a wall, equation 2.3 could be used and "weighted" for the respective wall area of the individual components. Wood studs installed 16 inches on center can comprise approximately 20-25% of a typical wall and if the studs were installed 24 inches on center they would comprise about 15-20% of a typical wall (Turner and Elder, 2001). This means that if the R-value of the wood studs is much less than the R-value of the other components of the wall, then the overall thermal resistance of the total wall is significantly lowered. Also, economics as well as the need for fire rated assemblies have increased the popularity of metal framing wall systems (Turner and Elder, 2001). Metal studs have a much lower thermal resistance than wood and can have nearly double the heat loss than that of a wood framed wall (Turner and Elder, 2001). Therefore, a wall constructed to be just as structurally sound as a wood or metal framed wall yet still have a high, uniform thermal resistance could significantly improve the energy efficiency of a building.

Insulated Concrete Forms (ICFs) are walls in which a concrete wall is poured into an insulated form similar to a styrofoam coffee cup. Poured concrete itself has a relatively low R-value, usually about R-0.5 per inch, as compared to steel or wood frames which have average R-values of R-7 and R-15 respectively (Energy Source Builder, 1994). The form then stays in place as a permanent part of the wall assembly. These insulated forms are what give an ICFs a higher R-value than steel or wood framed walls (DOE, 2005a). The forms can interlock or can be separate panels connected with plastic ties. Reinforcing bars can also be installed for earthquake or blast protection. The left-in-place forms not only provide a continuous insulation and sound barrier, but also a backing for drywall on the inside, and stucco, lap siding, or brick on the outside. ICF walls are more resistant to fire than a conventional wood framed wall, up to a 4 hour fire rating. ICF walls are also resistant to many pests such as rodents, termites, and insects. Many ICF manufacturers boast a uniform R-value of up to R-35 for their wall systems, as well as 30% to 50% less air infiltration than a conventional frame building (ICF Association, 2005). The Department of Energy estimates that facilities built with ICF exterior walls require an estimated 44% less energy to heat and 32% less energy to cool than comparable frame houses (DOE, 2005a). An example of an ICF wall can be seen in Figure 2.11.

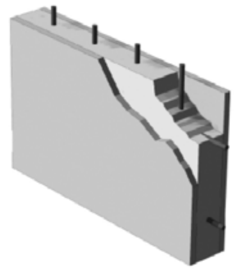

Figure 2.11: Cross section of a typical insulated concrete form wall (ICF Association, 2005). Concrete is poured between two insulated forms, which then stay in place as a permanent part of the wall assembly.

Structural Insulated Panels (SIPs) are very similar to ICFs in that they provide a uniform R-value across the entire wall. SIPs usually are comprised of a four to eight inch thick foam insulation core with a structural facing on each side. Common facings are drywall, oriented strand board (OSB), or plywood (DOE, 2005a). These wall systems can have an R-value of up to R-48, significantly reducing the heat transfer through them. They also have much less air infiltration than conventional wall systems. The Florida Solar Energy Center (FSEC) found a 12% to 17% energy savings from using SIP construction (DOE, 2005a). SIPs do not have the fire safety advantages or the blast protection of an ICF wall system however. An example of a SIP wall can be seen in Figure 2.12.

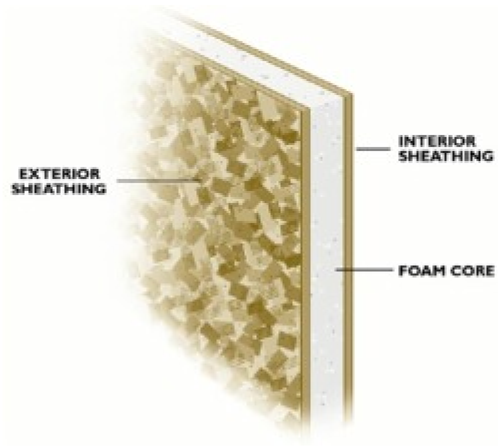

Figure 2.12: Cross section of a typical structural insulated panel wall (SIP Association, 2005). A foam core is sandwiched between two pieces of sheathing, giving a more uniform R-value across the wall.

2.4.4 Foundation

Because the foundation only accounts for about three percent of heat transfer in a building envelope (see Figure 2.3) and the relative difficulty of retrofitting the foundation of an existing building, this research will not explore the technologies available to make a foundation more energy efficient. However, many new buildings are being constructed using insulated concrete forms for their foundations to make them more energy efficient.

2.4.5 Landscaping

Carefully positioned trees around a building can save up to 25% of that buildings energy consumption for heating and cooling (DOE, 1995). Landscaping does this by reducing the surface temperature on the various building envelope components, therefore minimizing the temperature difference between the interior and exterior environments and minimizing the conductive heat transfer through the building envelope during the summer months. A well planned landscape can reduce an unshaded building’s summer energy costs anywhere from 15-50% (DOE, 1995). During the winter months the trees act as a windbreak, shielding the building from the convective heat transfer that occurs on a windy day. Studies have shown that these windbreaks can cut winter energy consumption by up to 40% (DOE, 1995). Landscaping strategies can vary depending in which climate region of the country the building is located. Temperate and warmer climates would use deciduous trees to block the solar heat during the summer and absorb it in during the winter months. Cooler and windy climates would use evergreen trees or shrubs to block heavy winds (DOE, 1995). Figure 2.13 shows a typical energy efficient landscape strategy for a temperate climate.

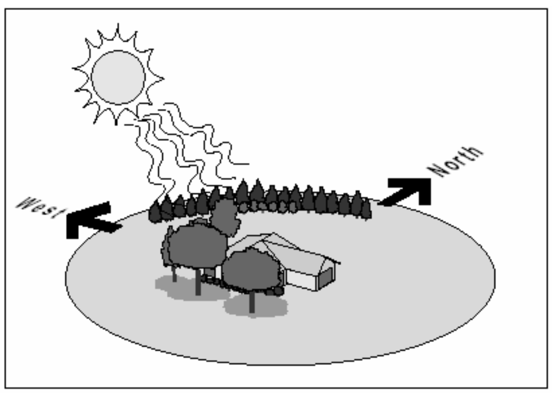

Figure 2.13: During the summer, tall spreading trees planted close to the building shade the roof. Broad, shorter leaves on the west side block the afternoon solar heat. A windbreak on the northwest side can shield the building from prevailing winter winds (DOE, 1995)

2.5 Considerations for Retrofitting Existing Buildings

There are many considerations to take into account when retrofitting an existing building with one of the building envelope technologies mentioned in the previous sections. The first is Indoor Air Quality (IAQ). Highly insulated buildings can accumulate noxious gases if they're not ventilated well. This is a problem known as sick building syndrome (SBS) (DOE, 2005c). IAQ must be taken into account when any part of the building envelope is retrofitted; making sure that the building is as properly ventilated as it was before the retrofit.

The second consideration is the cost of the retrofit. The Air Force ranks its energy conservation investment projects (ECIPs) on the basis of greatest potential life cycle cost payback (AFCESA, 2005b). Life cycle cost payback is calculated taking the cost of the retrofit and dividing that by the potential annual energy savings. The lower the payback, the better the value of the retrofit. If the payback period is greater than 10 years the project is not considered by the Air Force (AFCESA, 2005b).

The third consideration when retrofitting a building is the ease of construction and burden to the current building occupants. If the construction takes a long time or the technology has a high maintenance, it may actually make life in the building more difficult for the occupants. Aesthetics of the retrofit are another consideration for building occupants. If the retrofit is an eyesore, it can have a negative effect on the building occupants comfort.

The last consideration when retrofitting a building envelope is the safety benefit of the retrofit. One building envelope technology may have a higher fire rating or provide more blast or natural disaster protection over another. All of these considerations will be taken into account when the different building envelope technologies are evaluated.

2.6 Decision Analysis Background

Most day-to-day decisions can be made fairly easily and do not require in-depth analysis to reach an acceptable result. Situations such as these usually only require one decision to be made, even if there are multiple alternatives, and are known as “simple” decisions (Spradlin, 2005). An example of this would be someone choosing what to eat for dinner. Here, the decision maker is simply comparing different alternatives, and this type of decision does not require logical or mathematical models in order to achieve a satisfactory result. However, some decisions are more complex and require a systematic approach in order to objectively analyze them. Such decisions often have multiple competing objectives that require considerations of tradeoffs among those objectives, such as cost versus quality versus timeliness (Kirkwood, 1997:xi). Some of these objectives are quantifiable, such as cost and timeliness. However, some objectives cannot be quantified as easily, such as quality or aesthetics of a product.

Decision analysis is intended to help people deal with these difficult decisions (Clemen and Reilly, 2001:4). There are several different decision analysis methodologies in which these difficult decisions can be analyzed. Descriptive methods focus on how people actually make decisions (Clemen and Reilly, 2001:15), while normative methods are idealized theories assuming the decision maker is fully informed and rational (Keeney, 1993:xv). The focus of this research is to guide the decision maker (who may not be aware of the various energy efficient building envelope technologies) in selecting one or a combination of building envelope technologies and provide insight to make the best decision for a given DoD facility. Neither of these methods is appropriate for this research, therefore a prescriptive approach is required. Prescriptive models suggest how a decision maker should think about structuring objectives, making conflicting value tradeoffs, and about balancing various risks (Keeney, 1993:1). Most prescriptive decision analysis models are classified as either alternative focused thinking (AFT) or value focused thinking (VFT) models.

Alternative focused thinking models focus first on identifying the various alternatives of a given decision without first analyzing what is important to the decision maker. That is, no analysis is given to what the decision maker "values" as important in his decision. If none of the alternatives has what the decision maker truly values as important, then the best choice will only be the best of a poor lot (Kirkwood, 1997:43). Simply focusing on alternatives limits the way one thinks through a decision. This forces decision makers to be reactive to the alternatives presented before them, instead of being proactive and creating alternatives from what they desire out of the decision, or their "values." Alternatives are simply a means to achieving the decision maker's objectives in a decision problem (Keeney, 1992:viii). This flaw of AFT models led to the development of value focused thinking models. VFT models focus first on what values, or objectives, a decision maker is truly looking to gain in a decision. Values are the principles used for evaluation of consequences of a decision (Keeney, 1992:6). Thinking about values first is simply brainstorming without the constraints of alternatives. Without those constraints, more ideas can be generated, creating a "decision opportunity" rather than a decision problem (Keeney, 1992:7-8). Analysis of these values will not only determine if the alternatives of a decision are good or bad, it can uncover hidden objectives or even lead to the creation of new alternatives that may have not been originally considered. Keeney (1992:ix) states that VFT is different than AFT in three important ways. First, significant effort is given to articulating values. Second, this conveyance of values comes before any other activity in a decision problem. Third, these values are used to identify decision opportunities and create alternatives. Keeney's argument is that using VFT for a decision problem will create better decision situation and alternatives, which should lead to better consequences of that decision. Other benefits of VFT can be seen in Figure 2.14.

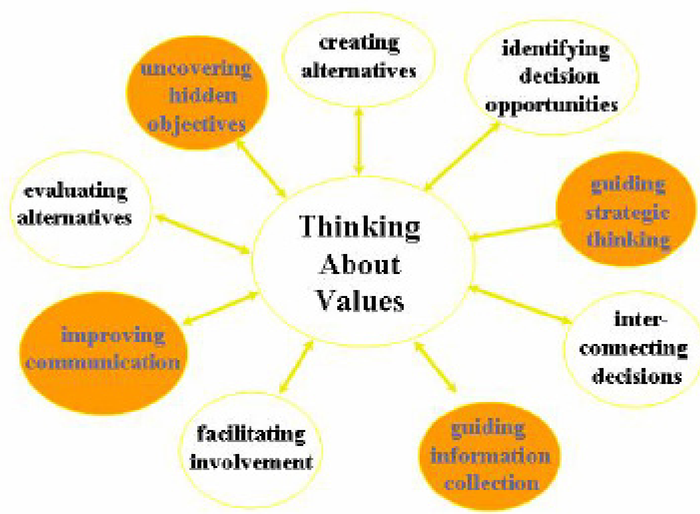

Figure 2.14: Various benefits of Value Focused Thinking (Staats, 2005)

Several papers have been published in the debate of whether Value Focused Thinking is truly a better decision analysis tool than Alternative Focused Thinking. Arvai, et al. (2001) found that people who use VFT make "more thoughtful, better informed, and higher quality decisions" than people who use AFT. Leon (1999) discovered that the VFT generated "a more extensive and hierarchical structure" than AFT. He also found that VFT covered more aspects of a decision problem than AFT, and overall the decision analysis structure generated by VFT "was equal or superior" to that generated by AFT. These papers concluded that by using VFT, people think more deeply about a decision problem than by using AFT. It allows decision makers to think about what they hope to gain in a decision, how to balance the varying tradeoffs that are prevalent in a complex decision and it also generates new ideas that may have not been previously thought of (Leon, 1999).

The VFT model developed by Keeney is comprised of five steps, listed below (Keeney, 1992:49).

Step1: Recognize a decision problem

Step 2: Specify values

Step 3: Create alternatives

Step 4: Evaluate alternatives

Step 5: Select an alternative

A ten-step process for Value Focused Thinking was developed for the Air Force Institute of Technology (Shoviak, 2001:63). Many of these steps are simply sub-steps of Keeney's original model. A brief description of the steps of this process is listed below, and will be discussed in more detail in Chapter 3.

Step 1: Problem Identification. This first step is for the decision maker to identify the decision situation and to understand his or her objectives in that situation (Clemen and Reilly, 2001:5). If this step is not executed properly, the decision maker could be attempting to solve the wrong problem. Sometimes surface issues hide the real problem. More often than not, people treat the symptoms of a problem instead of the problem itself. By not correctly identifying the right problem, the decision maker only wastes precious resources of time and money.

Step 2: Create the Value Hierarchy. Value hierarchies are value structures with a hierarchical or "treelike" structure (Kirkwood, 1997:12). An example of a value hierarchy is given in Figure 2.15.

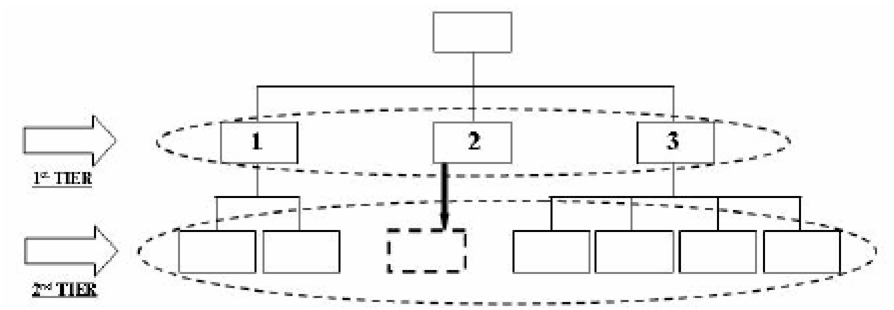

Figure 2.15: Example of a value hierarchy (Staats, 2005)

The top of the hierarchy is the decision to be made. The first tier under that is known as evaluation considerations, that is, what is important to the decision maker in regards to the overall objective of the decision. These are also known as fundamental objectives. The second tier consists of the measures in which the considerations will be evaluated (Kirkwood, 1997:13). These are known as means objectives, as they are the means to achieve the fundamental objectives (Keeney, 1992:35). Desirable properties for value hierarchies are listed below (Kirkwood, 1997:16-18).

1. Completeness: The evaluation considerations adequately cover all concerns to evaluate the decision.

2. Nonredundancy: No two evaluation considerations in the same tier should overlap.

3. Independence: The value assigned a score for one consideration cannot depend on the score of another consideration.

4. Operability: The hierarchy must be understandable for the person using it.

5. Small Size: Smaller hierarchies can be communicated more easily and are more operable.

Step 3: Develop Evaluation Measures. Evaluation measures are metrics for means objectives in the last tier of each branch of the value hierarchy. Evaluation measure scales can be classified as either natural or constructed, and also as either direct or proxy (Kirkwood, 1997:24). A natural scale is one that is known and used by everyone, such as profit measured in dollars. A constructed scale is one that is developed for a particular decision problem because no natural scale exists or is not appropriate for that problem. An example of a constructed scale would be temperature, although this scale has been in use long enough it can also be considered a natural scale. A direct scale measures the degree of attainment of an objective (such as profit in dollars) while a proxy scale measures the degree of attainment of an associated objective (such as Gross National Product measuring the economic well being of a country) (Kirkwood, 1997:24).

Step 4: Create Value Functions. A value function must be made in order to combine the measured values in the previous steps (which are usually in different units) into a common “value unit” on a scale of 0 to 1 (Kirkwood, 1997:61). The worst possible score for an evaluation measure would have a “value” of zero, while the best score for that measure would have a “value” of one. Intermediate values of scores between the extremes can be assessed directly from the decision maker (Shoviak, 2001:53). The product created from this process is called a Single Dimensional Value Function (SDVF).

Step 5: Weight the Value Hierarchy. As stated in Step 2, the value hierarchy is composed of many different objectives. These objectives may not all be of equal importance to the decision maker. Weights must be assigned to each of the objectives in order to account for this difference of importance (Shoviak, 2001:56). The process of assigning weights to objectives will be discussed in more detail in Chapter 3. It is important to understand the two different approaches of weighting: global and local. Global weighting is where weights are assigned to each of the bottom tier evaluation measures. They are assigned such that the sum of the weights is equal to one. The weights of the preceding tiers are then determined by summing the weights of the objectives beneath it. This is also known as a bottom up approach to weighting. (Jeoun, 2005:37). Local weighting is a process where weights are assigned to the first tier objectives first, and then weights are assigned to the evaluation measures beneath the first tier objectives so that they sum to one. The global weights can then be calculated by multiplying the local weights of each of the bottom tier evaluation measures by the local weights of the first tier objectives. This is also known as a top down approach to weighting (Jeoun, 2005:38).

Step 6: Alternative Generation. This step is where the decision maker determines which alternatives should be considered in the VFT model. Keeney (1992:202) suggests that the decision maker focus on one objective at a time and think of alternatives that might be very desirable if that were the only objective. This will most likely generate the largest number of alternatives, both good and bad. Then the decision maker must consider two objectives and try to develop alternatives that would be good for both, following by taking objectives three at a time and so on until all objectives are considered together. This will eventually create alternatives that are refinements of the original alternatives, and will allow the decision maker to eliminate undesirable alternatives. A different way to generate alternatives is a strategy generation table. An example of a strategy generation table is shown in Figure 2.16. In this example, an Air Force commander must generate a strategy to ensure air superiority. For each decision strategy theme, the commander must decide which aircraft to use, the number of aircraft, and which target to attack. The strategy generation table allows the decision maker to think more creatively about the problem and develop a combination of the alternatives not previously thought of (Shoviak, 2001:58).

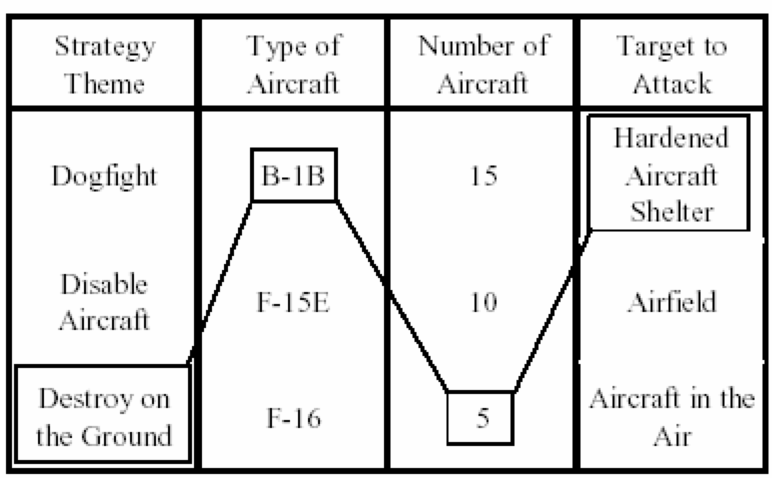

Figure 2.16: Example of a strategy generation table (Shoviak, 2001:58). This table allows decision makers to think more creatively about a problem and develop combinations of alternatives not previously thought of.

Step 7: Alternative Scoring. This is the step where data is collected from the decision maker. Values must be obtained for each evaluation measure in order to score each alternative and compare them to one another. This step will be described in more detail in Chapter 4.

Step 8: Deterministic Analysis. An overall value function is developed from the data gathered in the previous steps using computer software. This process will be described in more detail in Chapter 4.

Step 9: Sensitivity Analysis. The rank ordering of alternatives can significantly change when the weights of the evaluation measures are changed. This can provide the decision maker with valuable insight as to which alternative is the "best" depending on which objectives are more important. The weights are altered systematically by changing the weight of one objective, and adjusting the other weights to ensure they sum to one and also maintain the proportionality of the other weights to each other (Shoviak, 2001:61).

Step 10: Conclusions and Recommendations. This step is fairly straightforward. Conclusions and recommendations will be given to the decision maker based on the results of steps 8 and 9, as well as any insights gained during the analysis. This will be presented in Chapter 5.

2.7 Summary

Chapter 2 summarized a background of heat transfer theory and discussed the basic characteristics of a building envelope, including the common energy losses that building envelopes suffer and described new energy saving technology that can be retrofitted into an existing building to minimize these energy losses. Chapter 2 also explored the considerations a decision maker must face when retrofitting an existing building envelope, and compared various decision analysis methodologies. Lastly, this chapter explained why VFT is the most appropriate method for this research, and outlined the VFT process and desirable properties of a value hierarchy

III. Methodology

3.1 Overview

This chapter describes how the decision analysis method of Value Focused Thinking (VFT) was applied to the decision of choosing building envelope technologies to retrofit a given DoD building. It is worthy to note that the model created and values obtained from the decision maker are more important that the alternative chosen as the solution to the decision. This is because the model should be operable by many decision makers across DoD, and should be able to be used at the various locations around the United States with differing climate conditions and availability of the various building envelope technologies. Therefore, Steps 1 through 3 can be completed without regard to location, but Steps 4 through 10 must be made on a case-by-case basis, that is they must be modified when used at different locations (Schanding, 2004). VFT Steps 1 through 6 are included in this chapter, while Steps 7 through 9 are included in Chapter 4 and Step 10 is included in Chapter 5.

3.2 Ten Step VFT Process from Shoviak (2001)

3.2.1 Step 1: Problem Identification

As stated in Chapter 2, the identification of the problem at hand is of the utmost importance to ensure the correct problem is being solved. In this case, the problem is that the United States consumes more energy than it produces, and this furthers the United States' dependence on foreign sources of energy. There are two schools of thought to solve this problem. The first is to generate more energy from alternative sources in the U.S. The second is for America to use less energy. The White

House chose the latter, and mandated in EO 13123 that all federal agencies will use less energy. DoD currently has guidelines pertaining to the energy efficiency of new buildings being constructed, but there is no guidance on how to make the existing inventory more energy efficient. Since the average Air Force facility is over 40 years old, with 25% of the inventory being over 50 years old, (HQ AF/ILE, 2002), this research focuses on retrofitting the building envelope of an "average" Air Force facility. This research will provide military decision makers an objective decision analysis tool to select a building envelope technology that can be retrofitted into an existing DoD building and improve the energy efficiency of that facility. Specifically the research questions to be answered include:

1. What energy saving building envelope retrofit technologies are available for use and where have they been used successfully?
2. What do decision makers in the Department of Defense value in terms of building envelope performance and indoor air quality (IAQ)?
3. How much energy will be saved by incorporating these energy saving building envelope retrofit technologies?
4. What is the most appropriate policy vehicle to incorporate these technologies into existing buildings?

3.2.2 Step 2: Create the Value Hierarchy

As stated in Chapter 2, a value hierarchy is a value structure with a hierarchical or “treelike” structure (Kirkwood, 1997:12). Its purpose is to visually show what values of a decision are truly important to the decision maker. There are two approaches in creating a value hierarchy, top down and bottom up. A top down approach, also known as an objectives-driven approach, starts with the overall objective and subdivides this objective to develop the fundamental objectives and means objectives in successively greater detail (Kirkwood, 1997:21). This approach is normally used when the alternatives are not well known at the start of the analysis. Since the alternatives for this research were known at the start of the analysis, a bottom up, or alternative-driven approach was used. This approach examines the alternatives and how they differ. The means objectives are developed to determine the ways in which they differ, and these measures are grouped together to form higher layers of the value hierarchy (Kirkwood, 1997:20). Fundamental objectives are the objectives the decision maker truly seeks to gain from the decision being made, and means objectives are the “means” to achieve those fundamental objectives. For example, if a job seeker is comparing different employers to work for and his fundamental objectives are short term and long term financial security, the means to achieving those could include income, medical coverage, and cost of living in the area the job resides in (Kirkwood, 1997:22).

A thorough review of the current literature concerning energy saving building envelope technologies has shown that some of the main differences between building envelope technologies are their ability to resist heat transfer, how they may change the indoor air quality of the facility, and how much they cost to install and maintain. Some building envelope technologies also have higher fire ratings than traditional construction technologies. Discussions with the decision makers (Air Force Civil Engineer Operations

Flight Chiefs) and subject matter experts from AFCESA brought about more considerations, such as aesthetics, availability of maintenance personnel, and the life span of the technology. Other considerations were how difficult the technology is to retrofit into an existing facility and how long the building component being replaced has been in place. Lastly, the decision makers suggested that Anti-Terrorism/Force Protection (AT/FP) issues such as additional blast protection should be considered.

The overall value hierarchy in shown in Figure 3.1. The very top tier is the decision to be solved. To begin, the first tier or fundamental objectives were chosen. They included minimizing impact to the facility, improving the safety of the facility, and minimizing the resources used to install the new technology.

The “difficulty of construction” and “aesthetics” measures were grouped under the “facility impact” objective. This objective captures how the occupants of the facility are impacted by the decision to retrofit the building with a certain technology.

The “fire rating” and “blast protection” measures were grouped under the “building safety improvements” objective. This objective captures the value of improving the safety aspects of the building envelope components that are being considered for retrofit.

The “resources” objective refers to the organizations desire to use its resources in the most effective manner (Jeoun, 2005:42). The savings ratio, service availability, and percent of building component lifespan used measures were grouped under the resources objective.

Some building envelope technologies have a high installation and maintenance cost that is offset by high energy savings, while others do not pay themselves off in a timely manner. Others may have low installation and maintenance costs and pay themselves off quickly while some are inexpensive to install but don't add any additional energy savings benefits. Most organizations are limited in both budget and personnel; therefore, these resources should be allocated in the best way possible in order to minimize their impact to the organization.

The "Service Availability" measure refers to the whether there is maintenance service personnel in the local area (defined by location) that can service the technology being installed. The "percent of building component lifespan" measure refers to how much of a lifespan the building envelope component being replaced has remaining. For example, if a standard roof that has been used for 10 of its average 20 year lifespan is under consideration for replacement with a cool roof, it would have a value of 50% for this measure.

Each of these measures is explained in more detail in section 3.2.3.

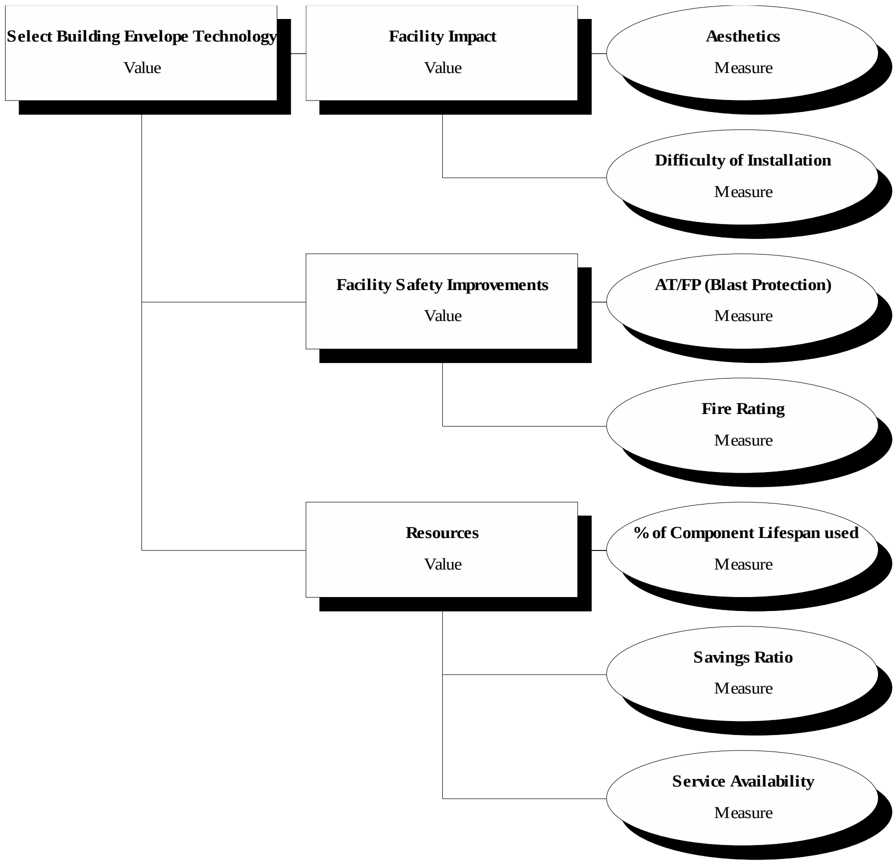

Figure 3.1: Value hierarchy for selecting building envelope technologies for retrofit into existing DoD buildings. There are three fundamental objectives including minimizing facility impact, improving facility safety, and minimizing resources used to install the technology.

3.2.3 Step 3: Develop Evaluation Measures

The qualitative value hierarchy created in Step 2 is useful to decision makers in collecting information about the decision, identifying and evaluating alternatives, and facilitating communication (Kirkwood, 1997:23). However, it is important to develop evaluation measures in order give the decision maker an unambiguous rating of how well an alternative does with respect to each objective (Kirkwood, 1997:24). More detail is given to each of the evaluation measures in the following sections.

As discussed in Chapter 2, evaluation measure scales can be classified as either natural or constructed, and also as either direct or proxy (Kirkwood, 1997:24). A natural scale is one that is known and used by everyone, such as profit measured in dollars. A constructed scale is one that is developed for a particular decision problem because no natural scale exists or is not appropriate for that problem. A direct scale measures the degree of attainment of an objective (such as profit in dollars) while a proxy scale measures the degree of attainment of an associated objective (Kirkwood, 1997:24).

For example, it is difficult to objectively compare the installation and maintenance costs of the various technologies, as they are usually measured in different units such as dollars per square foot of roof, or dollars per window installed. Therefore, a measure called "Savings Ratio" was constructed to capture the total installation cost in dollars, as well as the present value of maintenance costs and energy savings over a timeframe of ten years.

3.2.3.1 Aesthetics

This is a constructed, direct measure with three categories. The categories are obtrusive, neutral and improves aesthetics. This measure is quite subjective, as many people perceive aesthetics differently. In order to truly gauge this value, a poll of the buildings occupants or the workers on the base would have to be taken. The value that gains the most votes from the poll would be taken as the value for the measure. For this research, Microsoft© Excel Random function was used to determine the value, since a generic facility is being used and interviews are not feasible. Typically, the value of "improves aesthetics" is more preferred to the value of "obtrusive."

3.2.3.2 Difficulty of Installation

This measure is a constructed, proxy measure with three categories. These categories are easy (one to seven days), medium (eight to twenty one days), and hard (over 21 days). This consideration measures the amount of discomfort the building occupants must suffer because of the difficulty of the installation. Longer installations are generally more of a burden to the occupants, and may actually require displacement of the occupants, while easy installations may be barely noticeable by the building occupants. Therefore, values of "easy" installation are more preferred to values of "hard" installation.

3.2.3.3 Blast Protection

This is a constructed, direct measure with two categories. The categories are "improves fire blast protection" or "no change in blast protection". The values will be taken from the literature review. "High blast protection" as defined by the military is "no damage to facility" from a blast within 33 feet of the facility (Reward Walls, 2003). Usually the value of "improves blast protection" is more preferred to the status quo of no change in blast protection.

3.2.3.4 Fire Rating

This is a constructed, direct measure with two categories. The categories are "improves fire rating" or "no change in fire rating." The values will be taken from the literature review. Fire Ratings are based in hours, such as quarter hour, half hour,

hour, two hours, and so forth. For instance, this means a particular material with a one hour fire rating should theoretically be able to withstand a fire for one hour without destruction. Usually the value of ”improves fire rating” is more preferred to the status quo of no change in fire rating.

3.2.3.5 Percent of Building Component Lifespan used

This is a constructed, direct measure that takes into consideration the amount of life the building component being replaced has left. For instance, if a roof with a 20-year lifespan has only been in place for 10 years, it has used 50% of its lifespan. Typically values near 100% are more preferred and values less than 50% are less preferred by decision makers; there is no reason to remove a perfectly good roof.

3.2.3.6 Savings Ratio

This is a constructed, proxy measure. This measure includes the total installation cost of the retrofit, plus the present value of the maintenance costs and energy savings over a period of ten years. Ten years is the amount of time that AFCESA recommends an energy project should pay itself off in energy savings. In other words, energy projects should have a payback period of 10 years or less according to AFCESA. The savings ratio equation is shown in equation 3.1 (CFR, 2000b).

$$\text{Savings Ratio} = \frac{\text{Present Value(Energy Savings)}}{\text{Installation Costs} + \text{Present Value(Maintenance Costs)}} \qquad (3.1)$$

Where:

$$\text{Present Value(FV)} = \sum_{n=\text{year costs occur}} (FV)(1+i)^{-n} \quad \text{(3.2) (Turner and Elder, 2001:45)}$$

Where:

PV = Present Value ($)

FV = Future value of maintenance cost or energy savings ($)

i = rate of inflation (decimal, assumed to be 0.0349 (Inflation Data, 2006)

n = year of annual cost or savings

The energy savings occur in every year through year ten (and beyond), while maintenance costs for green roofs occur only for the first two years (University of Wisconsin-Milwaukee, 2006) and maintenance costs for Cool Roofs only occur in year ten (Santee Cooper, 2006). Installation costs, maintenance costs, and energy savings are all dependant on the size and type of facility in question. This research will use a generic office facility as defined by AFCESA as being a “typical” Air Force facility in order to gather this data. This generic facility is a two story, 25,000 square foot office building. It has a 3-ply built-up roof with on a steel deck, masonry exterior with steel studs, and single paned windows and aluminum frames. A schematic of this facility and all its construction details can be seen in Appendix A. Installation and annual maintenance cost data will be taken from estimates of the average costs for the continental United States (from literature review). Energy Savings data will be taken from an energy simulation program called EQuest using the generic facility and weather data from specific locations.

A savings ratio of 1 would suggest that the energy savings would pay for the retrofit within 10 years, or have a 10 year payback as preferred by AFCESA. Anything less than that would be unfavorable according to AFCESA, and anything above would be extra justification to retrofit the building.

3.2.3.7 Maintenance Service Personnel Availability

This measure is a constructed, proxy measure with two categories. The categories are available (as defined as maintenance personnel available in the local area, which is location dependant) and unavailable (maintenance personnel not available within the local area.). This measure captures the value of having a fast response from the personnel responsible for installation and maintenance of the building envelope component in question. As mentioned above, the definition of “local area” is dependant on the location of the Air Force base. The local area of a base on an island in the Pacific Ocean or overseas country is much different than the local area of a CONUS base. The value of “available” is typically more preferred than the value of ”unavailable” at any location however.

3.2.4 Step 4: Create Single Dimension Value Functions

A single dimension value function (SDVF) must be created in order to convert each of the evaluation measures into a unitless value between zero and one. Two types of value functions are commonly used: piecewise linear (discrete) and exponential (continuous). A piecewise linear value function is used when the evaluation measure being considered has a small number of possible scoring levels (such as a measure with two or three categories). Otherwise, an exponential value function is the preferred method (Kirkwood, 1997:61).

Piecewise linear value functions were used for the evaluation measures of aesthetics, difficulty of installation, fire rating, blast protection and service availability. The evaluation measures of savings ratio and percent of building component lifespan used were exponential value functions. Regardless of the type of value function used, all SDVF's have monotonicity, that is higher levels of an evaluation measure are always more preferred or less preferred (Kirkwood, 1997:65)

The equation for monotonically increasing exponential value function is shown in equation 3.3, and the equation for a monotonically decreasing exponential value function is shown in equation 3.4 (Kirkwood, 1997:65-66).

$$v(x) = \begin{cases} \dfrac{1 - \exp[-(x - Low)/\rho]}{1 - \exp[-(High - Low)/\rho]}, \rho \neq Infinity \\ \dfrac{x - Low}{High - Low}, otherwise \end{cases} \qquad \text{Eq 3.3}$$

$$v(x) = \begin{cases} \dfrac{1 - \exp[-(High - x)/\rho]}{1 - \exp[-(High - Low)/\rho]}, \rho \neq Infinity \\ \dfrac{High - x}{High - Low}, otherwise \end{cases} \qquad \text{Eq 3.4}$$

Where:

v(x) = the exponential value function

High = the upper bound of the evaluation measure

Low = the lower bound of the evaluation measure

ρ = the exponential constant of the value function *exp* = the exponential function (e^x, or 2.7182^x)

The single dimension value functions for each of the evaluation measures can be seen in Appendix A. An example of a piecewise linear and exponential single dimension value function can be seen in Figure 3.2.

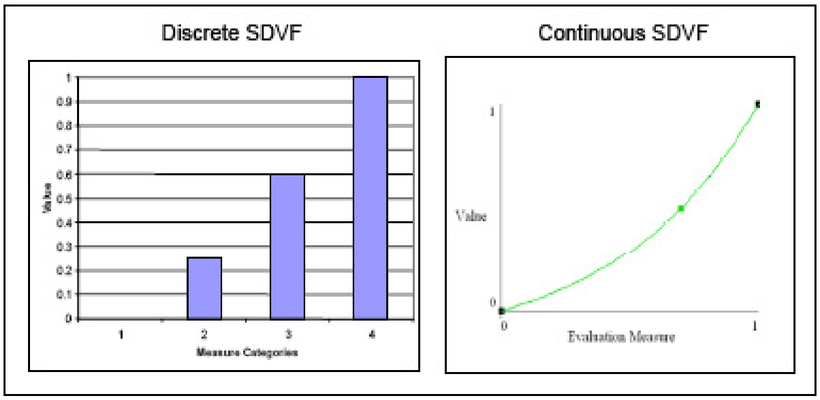

Figure 3.2: Example of a Piecewise Linear (Discrete) and Exponential (Continuous) SDVF (Jeoun, 2005)

3.2.5 Step 5: Weight the Value Hierarchy

In order to take into account the varying levels of importance of each of the defined evaluation measures, the decision maker must weight the value hierarchy. The value hierarchy was weighted using the global weighting process as described in Chapter 2. A process known as swing weighting was employed. This is a process where the decision maker ranks the measures in order of importance from least to most important. A variable is assigned as the weight of the least important measure, and the remaining measures are assigned weights that are multiples of that variable. The weights are then summed and the total is put equal to one. From there, simple algebra determines the value of the variable and hence the values of the weights for all measures (Kirkwood, 1997:70). Although all decision makers were shown the same value hierarchy, they each weighted the hierarchy differently. This can lead to very different conclusions as to which technology should be installed in the generic facility. A list of the weights of all measures is shown in Table 3.1.

Table 3.1: Global weights of measures for each decision maker in various climates

Measure	Northeast Climate	Southeast Climate	Central Climate
Aesthetics	6.80%	26.1%	20.8%
Difficulty of Installation	10.20%	21.7%	8.4%
AT/FP (Blast Protection)	13.60%	8.70%	12.5%
Fire Rating	3.30%	4.3%	4.20%
Building component % of lifespan	20.30%	13.00%	12.5%
Savings Ratio	32.20%	21.7%	20.8%
Service Availability	13.60%	4.3%	20.8%

3.2.6 Step 6: Alternative Generation

As stated in Section 3.2.2, the value hierarchy was developed from the bottom up, meaning that the alternatives were known at the beginning of the process. The alternatives for this research were discussed in Chapter 2, and they include triple paned low-emissivity windows, triple paned windows with inert gas (argon), triple paned windows with air gap, nylon/fiberglass window frames, extensive green roofs, cool roofs, landscaping, structural insulating panels and insulating concrete forms. Most of these alternatives were listed as possible building envelope technologies to use in new construction on the Department of Energy's Office of Energy Efficiency and Renewable Energy Building Envelope website (DOE, 2005b). Other alternatives that were not listed there (such as green roofs) were developed through a thorough review of the current literature on building envelope technologies and discussed amongst the decision makers and Air Force subject matter experts as possible technologies to use in Air Force facilities. Lastly, some alternatives were combined to make new alternatives, such as the ICF-SIP Superwall, Green Roofs with an SIP, and Cool Roofs with an SIP. These new alternatives were also found to be used in the commercial industry. One alternative that was originally to be included (landscaping) was taken out of consideration due to the fact that it was not possible to simulate the energy savings in EQuest. A complete list of all fifteen alternatives can be seen in Table 3.2.

Table 3.2: Fifteen alternatives generated for this research

Green Roof (Extensive)
Green Roof w/ SIP
Cool Roof (Coating)
Cool Roof (Single Ply)
Cool Roof w/ SIP
New BUR w/ SIP
Triple Paned Window, Low-e 1/8” glass, 1/2" air gap, vinyl frame
Triple Paned Window, 1/8” glass, 1/2" argon gap, vinyl frame
Triple Paned Window, 1/8” glass, Low-e, 1/2" argon gap, vinyl frame
Triple paned window, 1/8” glass, Low-e film, 1/2" air gap, vinyl frame
Double paned window, 1/4" glass, 1/2" air gap, aluminum frame
Triple paned Window, 1/8” Glass, 1/2" air gap, vinyl frame
ICF
SIP
SIP-ICF Superwall

IV. Results and Analysis

4.1 Overview

This chapter explains three of the remaining four steps in Shoviak's Ten Step VFT Process. Step 7 is a presentation of the results from scoring the alternatives, while Step 8 is a deterministic analysis of the scores to explain why a certain alternative scored higher or lower than another. Lastly, Step 9 is a sensitivity analysis of the various scores to determine if a change in the global weights of a particular measure would have an effect on the overall ranking of the alternatives. This research was conducted at several locations (Arizona, Colorado, and Delaware) in order to see the effects of different climates, as well as different decision makers on the rankings of the alternatives. Because of this, the results for each step are presented separately for each installation (Jeoun, 2005).

4.2 Southwest AFB

4.2.1 Step 7: Alternative Scoring at Southwest AFB

The location of Southwest AFB is near Phoenix, Arizona. This location has a relatively dry climate and an annual mean temperature of 72.6 °F. The average annual percentage of possible sunshine at this location is 85% (Schmidli, 1996). Data had to be obtained from various sources in order to score each of the alternatives. Some data could not be obtained directly since the decision analysis model is based on a generic facility. Because of this, data for the "aesthetics" measure and "percent of building component lifespan" measure was obtained using the Microsoft Excel© Random function. A random number between one and three was chosen for the "aesthetics" measure, one being "more pleasing," two being "neutral," and three meaning " less pleasing." Some alternatives that cannot be seen when installed (such as SIP and ICF walls) were automatically given a "neutral" score. For the "percent of building component lifespan" measure a random number between zero and one hundred was chosen as the percent lifespan for the component being considered for replacement. When using this model for an actual facility, data should be readily available for the "percent of building component lifespan" measure, and can be obtained for the "aesthetics" measure by taking a simple poll of the building occupants to see if they find the new technology aesthetically pleasing or not.

The energy data was obtained using an energy simulation program called EQuest, which is a Microsoft© Windows based program based on the popular DOE-2 energy simulation software. The total energy used for the baseline generic facility was simulated, then again with each of the new building envelope technologies installed. By doing this the total energy saved in kilowatt-hours (kWh) and British Thermal units (BTUSs) was calculated and a total energy cost saved in dollars determined. The climate data for Phoenix, Arizona was downloaded from the EQuest website for this simulation. That information plus the installation and maintenance costs were used in Equation 3.1 to determine the value for the "savings ratio" measure. Values for the "difficulty of installation," "blast protection" and "fire rating" measures were obtained from a review of the current literature on the various building envelope technologies. Lastly, values for the "service availability" measure were obtained from a review of local contractors near each installation. This building and energy data was then input into a decision analysis program called Logical Decision©, which performed the alternative scoring and sensitivity analysis. Table 4.1 shows the final data for the alternatives at Southwest AFB.

Table 4.1: Building and Energy Data for Alternatives at Southwest AFB

Alternative	"SAVINGS RATIO"	Aesthetics	Blast Protection	Fire Rating	Building Component % Lifespan	Difficulty of Installation	Service Availability
Green Roof (Extensive)	0.05	3	No	no	87	3	unavailable
Green Roof w/ SIP	0.05	2	No	yes	87	3	unavailable
Cool Roof (Coating)	0.75	1	No	no	87	1	local
Cool Roof (Single Ply)	0.37	2	No	no	87	3	local
Cool Roof w/ SIP	0.35	2	No	yes	87	3	local
New BUR w/ SIP	0.01	1	No	yes	35	3	local
Triple paned Low-e Window 1/2" air gap, vinyl frame	1.75	1	No	no	35	2	local
Triple paned window 1/2" argon gap, vinyl frame	1.66	2	No	no	35	2	local
Triple paned window, Low-e w/ 1/2" argon gap, vinyl frame	1.81	1	No	no	35	2	local
Triple paned window, Low-e film 1/2" air gap, vinyl frame	1.72	2	Yes	no	35	2	local
Double paned window, 1/2" air gap aluminum frame	1.70	2	No	no	35	2	local
Triple paned window, 1/2" air gap vinyl frame	1.55	1	No	no	35	2	local
ICF	0.03	2	Yes	yes	2	3	local
SIP	0.03	2	No	yes	2	3	local
SIP & ICF Wall	0.03	2	Yes	yes	2	3	local

Logical Decision© uses a function called the "additive value function" to score the different alternatives. In this function, each measure is assigned a single dimension value function (SDVF) as well as a weight. The value function for each measure is the product of its SDVF value and its weight, and the additive value function is the sum of value functions for each measure (see Equation 4.1) (Kirkwood, 1997:72).

$$v(x) = \sum_{i=1}^{n} \lambda_i v_i(x_i) \qquad (4.1)$$

Where:

$v(x)$ = the total score for alternative x

λ_i = the weight for measure i (all weights must sum to 1)

$v_i(x_i)$ = SDVF for measure i

x_i = the score for alternative x on measure i

n = the total number of measures

As stated in Chapter 2 and 3, these values are between zero and one, with one being more preferred and zero being less preferred. Figure 4.1 presents the scores for the alternatives at Southwest AFB. Overall for this facility at this location, the triple paned window with low-e film, 1/2" air gap and vinyl frame is the most preferred alternative with a score of 0.494.

Alternative	Value
Triple paned, low-e film, 1/2" air, vinyl	0.494
Triple paned, low-e, 1/2" air, vinyl	0.488
Triple paned, low-e, 1/2" argon, vinyl	0.429
Cool Roof Coating	0.426
Double paned, 1/2" air, aluminum	0.418
Triple paned, 1/2" argon, vinyl	0.415
Triple paned, 1/2" air, vinyl	0.339
Cool Roof Single Ply	0.336
Cool Roof w/ SIP	0.271
Green Roof w/ SIP	0.213
New BUR w/ SIP	0.210
Green Roof, Extensive	0.209
SIP	0.122
SIP/ICF Superwall	0.089
ICF	0.057

Figure 4.1: Alternative Scoring at Southwest AFB

4.2.2 Deterministic Analysis for Southwest AFB

Deterministic analysis of the alternative scores will give the decision maker more insight as to why certain alternatives scored well and others scored poorly. Since the additive value function is simply the sum of the weighted SDVF's for each measure, it is possible to see why each alternative scored the way it did. Figure 4.2 displays the alternative scores into their respective weighted SDVF.

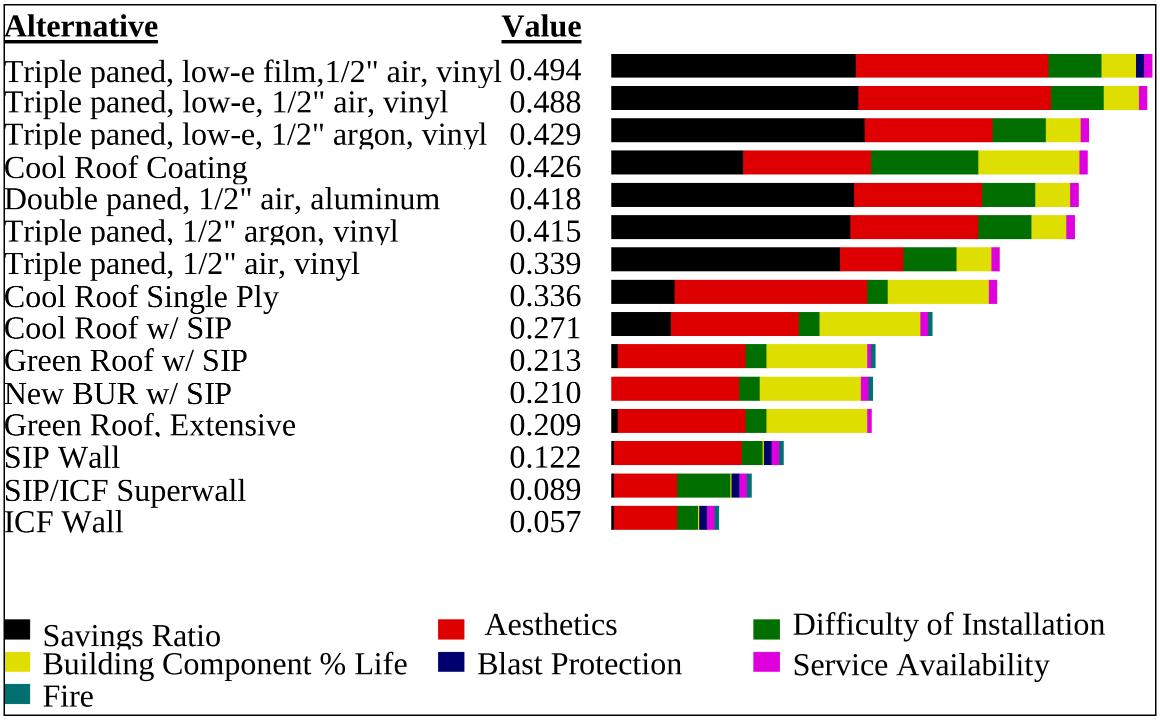

Figure 4.2: Alternative scores displayed with weighted SDVFs for Southwest AFB

It is easy to see where each alternative scored well and where they scored poorly from Figure 4.2. Each of the window alternatives scored well in the Savings Ratio measure because of their lower cost and higher energy savings, and also because the savings ratio was the measure that was weighted second highest by the decision maker (21.7%). The only measure weighted higher was Aesthetics (26.1%). The window technologies also scored well in the difficulty of installation measure, since they would install relatively quickly without burden to the building occupants. The triple paned windows with low-e film and 1/2" air gap scored higher than the regular triple paned low-e windows with a 1/2" air gap because the low-e film has the added benefit of blast protection. It is interesting to note that the only roofing technology to score as high as the window technologies was the cool roof coating. It scored well because it was inexpensive to install and maintain, and it could be easily installed without disruption to the building occupants. It is also interesting that the double paned windows with aluminum frames scored higher than some triple paned windows with vinyl frames. This is because the double paned windows (which most new construction in the Air Force has (AFCESA, 2005a)) have a higher savings ratio; that is they cost less to install then the triple paned windows and have good energy savings, though not as high as the triple paned windows. The other roofing technologies had good energy savings but they were simply too expensive to install, driving the savings ratio down. They also scored poorly on the difficulty of installation measure, since the installation time would likely be 30 days or more. Lastly, the wall technologies simply did not save enough energy as compared to their installation costs to make them a worthwhile choice. Their installation costs are similar to a typical stick built facility, making them a good choice for new construction. However, their costs do not justify their energy savings for retrofitting an existing facility. All of the data for these calculations can be seen in Appendix A.

4.2.3 Sensitivity Analysis for Southwest AFB

Sensitivity analysis of the weights of each measure was performed to provide insight to the decision maker as to the impact of the rank ordering (if any) of the alternatives if the weights of the measures were changed. As discussed in Chapter 3, these weights reflect the importance of each measure to the decision maker, and can sometimes be a matter of disagreement if there are multiple decision makers (Kirkwood, 1997:82). Sensitivity analysis on the weights is done by changing the weights of one measure and still keeping the sum of all the weights equal to one. Algebraic manipulation is required to calculate the weights of the remaining measures. For example, if there were three measures in a VFT model (measure X, Y, and Z) and sensitivity analysis was conducted on the weight of X, measure X's weight would be varied between 0 and 1 and the equation for the measures Y and Z's weight would be as follows (Kirkwood, 1997:82):

$$\lambda_Y = (1 - \lambda_X)\left(\frac{\lambda_Y^o}{\lambda_Y^o + \lambda_Z^o}\right) \qquad (4.2)$$

$$\lambda_Z = (1 - \lambda_X)\left(\frac{\lambda_Z^o}{\lambda_Z^o + \lambda_Y^o}\right) \qquad (4.3)$$

Where:

λ_X = new weight of measure X

λ_Y = new weight of measure Y

λ_Z = new weight of measure Z

λ_Y^o = original weight of measure Y

λ_Z^o = original weight of measure Z

First, sensitivity analysis was conducted on the fundamental objectives to see if they were sensitive to any changes in the weighting. If they were found to be sensitive, meaning the rank ordering of the alternatives changes within a realistic changing of the weights (Jeoun, 2005), then sensitivity analysis was conducted on the means objectives to see which measure is sensitive to these changes in weightings.

4.2.3.1 Sensitivity Analysis of Facility Impact Objective at Southwest AFB

The best alternative (triple paned windows with low-e film, 1/2" air gap and vinyl frame) remained the top choice for any variation in the weighting of the facility impact objective. Therefore, the facility impact objective was found to be insensitive to changes in its weight of importance. It is interesting, however, that as the weight on facility impact was varied from 0 to 1, the ranking for the cool roof coating alternative goes from being seventh best to being third best. This is because it scored well on the difficulty of installation measure. The sensitivity analysis for the facility impact objective can be seen in Figure 4.3.

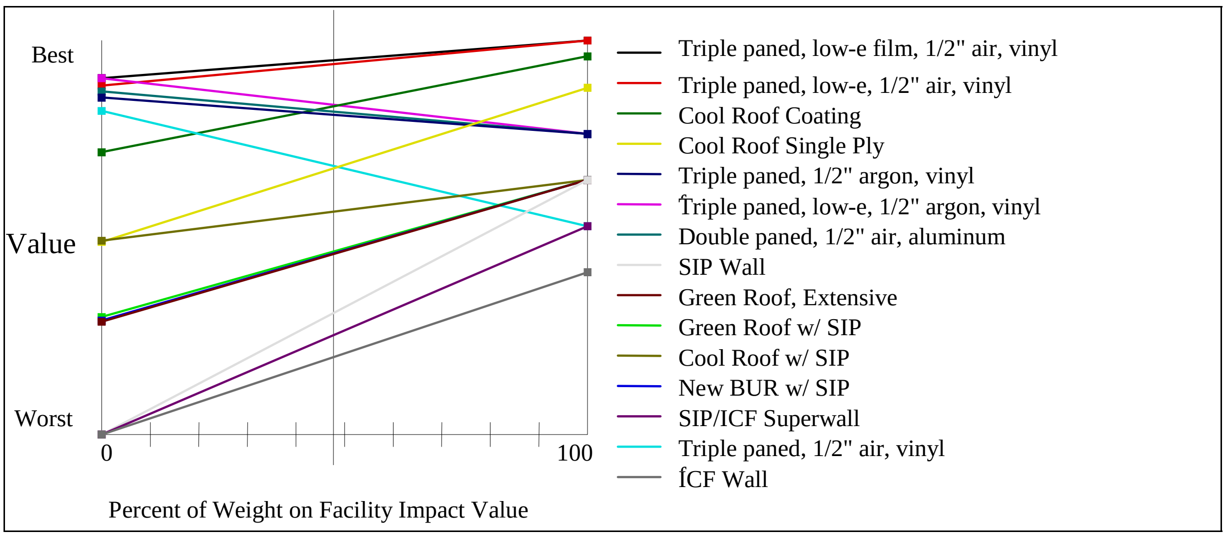

Figure 4.3: Sensitivity Analysis of Facility Impact Objective at Southwest AFB

4.2.3.2 Sensitivity Analysis of Facility Safety Improvements Objective at Southwest AFB

The Facility Safety Improvements objective was also insensitive to varying the weight of this measure. The most preferred alternative (triple paned windows with low-e film, 1/2" air gap and vinyl frame) did not change until the weight was increased from 13% to 93%. This is where the wall technologies that improve blast protection and increase the fire rating of the facility take over as being more preferred. Since this dramatic change in weight is unrealistic, the objective is found to be insensitive. The sensitivity analysis for this objective can be seen in Figure 4.4

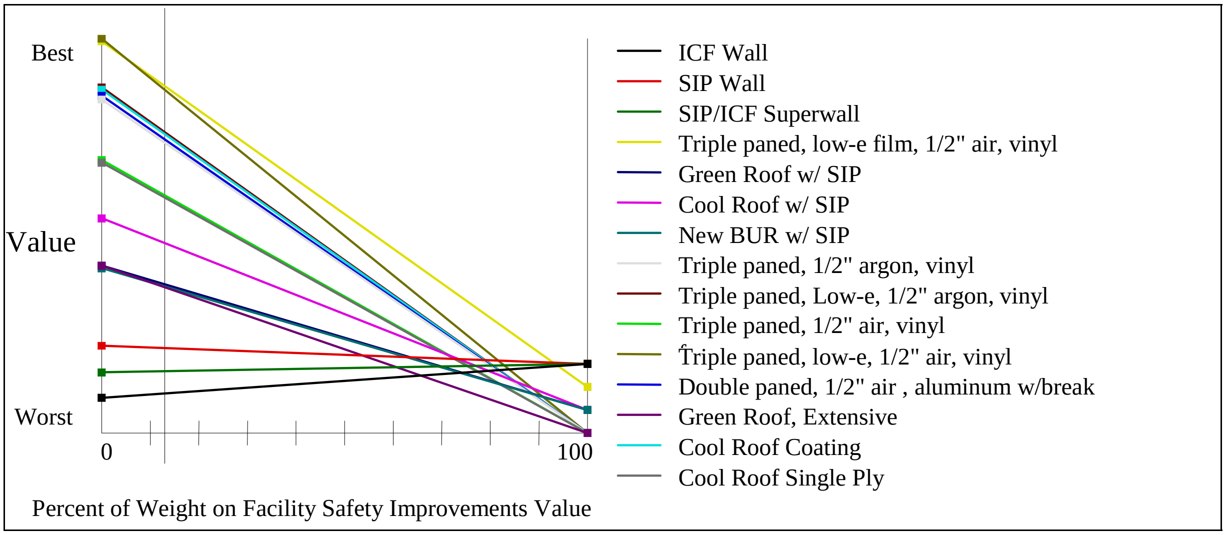

Figure 4.4: Sensitivity Analysis of Facility Safety Improvements Objective at Southwest AFB

4.2.3.2 Sensitivity Analysis of Resources Objective at Southwest AFB

This objective is also fairly insensitive when the weight is varied. Figure 4.5 shows that the low-e film alternative is the best alternative (or tied for best) until the weight is increased from 39% to approximately 85%. Even as the weight of this objective is increased to 100%, the low-e film alternative is no worse than the third best alternative. That means that no matter what the weighting of Resources, the low-e film is still a very viable option. Figure 4.5 also shows that as the weight of resources is increased, the window technology alternatives tend to be the best and the wall and roof technologies do not fare very well. This is because of their very low score in the Savings Ratio measure.

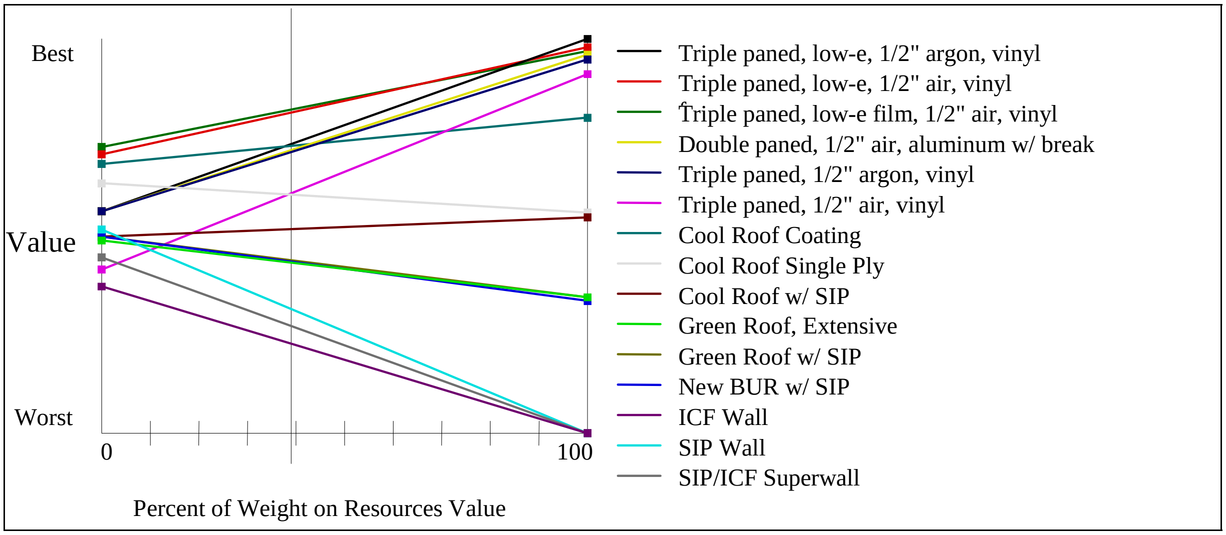

Figure 4.5: Sensitivity Analysis of Resources Objective at Southwest AFB

Since the three fundamental objectives were found to be insensitive to changes in their weighting, no further analysis of the means objectives is required.

4.3 Central AFB

4.3.1 Alternative Scoring of Central AFB

Central AFB is located in Denver, Colorado. The average annual temperature in Denver is 50.3 °F. The average annual percentage of possible sunshine at this location is 69% (Western Regional Climate Center, 2006). Table 4.2 shows the final data for the alternatives at Central AFB. More details about this data can be found in Appendix A.

Table 4.2: Building and Energy Data for Alternatives at Central AFB

Alternative	"SAVINGS RATIO"	Aesthetics	Blast Protection	Fire Rating	Building Component % Lifespan	Difficulty of Installation	Service Availability
Green Roof (Extensive)	0.00	3	no	no	91	3	local
Green Roof w/ SIP	0.02	2	no	yes	91	3	local
Cool Roof (Coating)	0.01	2	no	no	91	1	local
Cool Roof (Single Ply)	0.00	2	no	no	91	3	local
Cool Roof w/ SIP	0.04	1	no	yes	91	3	local
New BUR w/ SIP	0.05	3	no	yes	91	3	local
Triple paned windows, Low-e, 1/2" air, vinyl frame	2.23	2	no	no	1	2	local
Triple paned windows, 1/2" argon, vinyl frame	1.65	3	no	no	1	2	local
Triple paned windows, Low-e, 1/2" argon, vinyl frame	2.70	3	no	no	1	2	local
Triple paned window, Low-e film, 1/2" air, vinyl frame	2.06	2	yes	no	1	2	local
Double paned window, 1/2" air, aluminum frame w/ break	2.29	2	no	no	1	2	local
Triple paned window, 1/2" air, vinyl frame	2.36	3	no	no	1	2	local
ICF	0.31	2	yes	yes	92	3	local
SIP	0.20	2	no	yes	92	3	local
SIP & ICF	0.20	2	yes	yes	92	3	local

The final value scores for the alternatives at Central AFB can be seen in Figure 4.6. The best alternative is the Triple paned window, low-e, with 1/2" argon gap and vinyl frames with a total value score of 0.693. It is notable, however, that the second and third best alternatives are only one one-thousandth difference from the best alternative, making them all good choices. Similarly to Southwest AFB, most of the window technologies were better alternatives than the roof or wall technologies.

Alternative	Value
Triple paned window, low-e, 1/2" argon	0.693
Triple paned window, 1/2" air	0.692
Triple paned window, 1/2" argon	0.691
Triple paned window, low-e film, 1/2" air	0.581
New BUR w/ SIP	0.547
Green Roof, Extensive	0.547
Double paned window, 1/2" air, alum	0.525
Triple paned window, low-e, 1/2" air	0.525
Cool Roof Coating	0.462
ICF	0.451
SIP	0.451
ICF-SIP Superwall	0.451
Green Roof w/ SIP	0.380
Cool Roof Single Ply	0.380
Cool Roof w/ SIP	0.338

Figure 4.6: Alternative scoring at Central AFB

4.3.2 Deterministic Analysis of Central AFB

Figure 4.7 shows each of the alternatives respective weighted SDVF. The window technologies scored higher mostly because of their high score in the savings ratio measure. Unfortunately even from this figure it is hard to determine how the best alternative differs from the second and third best alternative. Table 4.2 shows that all measures have the same values for these three alternatives except for savings ratio. The triple paned low-e windows with 1/2" argon gap and vinyl frames have the highest savings ratio (2.7), followed by the triple paned windows with 1/2" air gap (2.36) and then the triple paned windows with 1/2" argon gap (1.65). Since the decision maker's SDVF gave a value of 0.99 for a savings ratio of 1 and a value of 1 for a savings ratio of

2 (see Appendix A for this SDVF), it makes sense that this additional energy savings adds little to the total value of the building technology. However the triple paned low-e windows with 1/2" argon gap is still the better choice because it will save more energy and money than the other two windows.

The decision maker for Central AFB weighted the measures of aesthetics and service availability the same as savings ratio (20.8%), therefore some of the roofing technologies scored well in those areas, as well as in service component percent lifespan, giving them a high enough overall score to compete with some of the window technologies. The wall technologies couldn't make up for their poor score in the savings ratio measure however, and they all scored near the bottom for Central AFB.

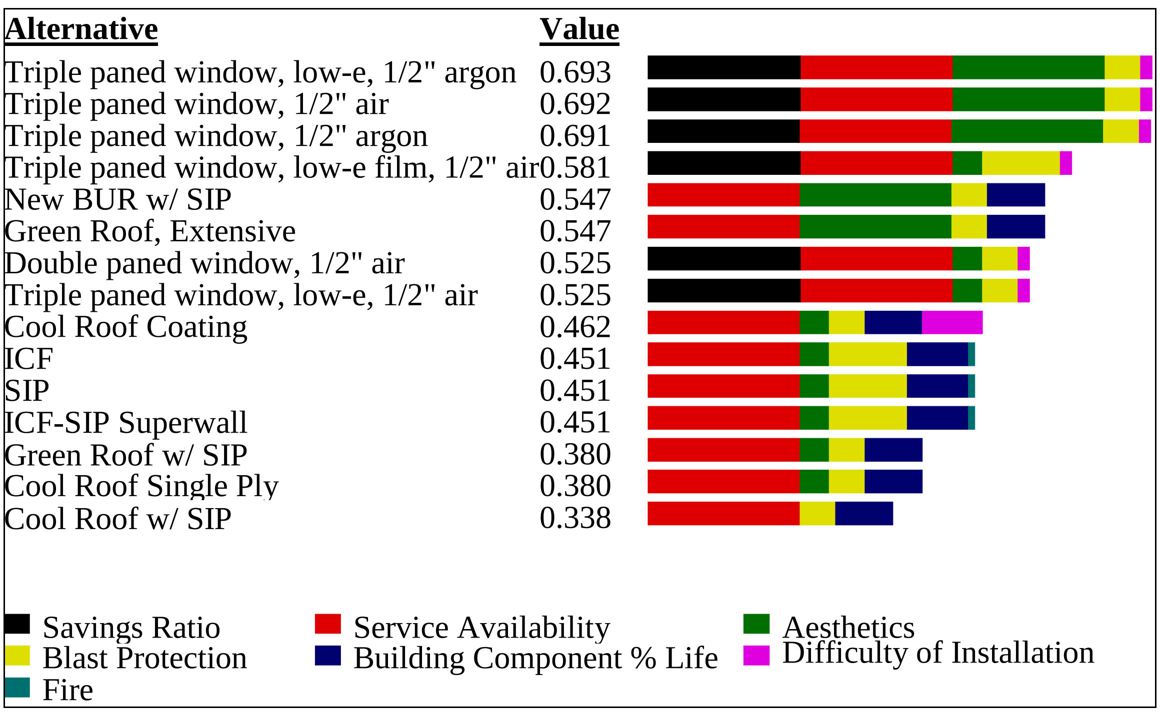

Figure 4.7: Alternative scores displayed with weighted SDVFs for Central AFB

Another technique to gain insight into the value model and see how the alternatives really perform against one another is to compare the actual and effective weights of the means objectives (Jeoun, 2005). The actual weight is the weight initially placed on the measure by the decision maker. The effective weight is what the weight of a measure would be if the projected range of a measure equaled the actual observed range of the alternatives (Jeoun, 2005). For example, consider the measure, service availability. Figure 4.8 shows that it has a high actual weight (20.8%, tied with savings ratio and aesthetics). But the effective weight of this measure is zero, because all of the alternatives scored the same value for this measure (local area, value of 1). In essence, this measure has no influence on the rankings of the alternatives. Figure 4.8 displays the actual and effective weights for all of the means objectives for Central AFB. From this figure one can see that the savings ratio and aesthetics measures make up for over 64% of the total effective weight for the model.

Measure	Percentage Weight	Effective Weight
AT/FP (Blast Protection)	12.5	8.656
Aesthetics	20.8	32.009
Building Component % of Useful	12.5	12.822
Difficulty of Installation	8.3	12.676
Fire Rating	4.2	1.600
Savings Ratio	20.8	32.237
Service Availability	20.8	0.000

Figure 4.8: Actual and effective weights for means objectives at Central AFB

4.3.3 Sensitivity Analysis of Central AFB

As in section 4.2.3, sensitivity analysis was first performed on the fundamental objectives to determine what changes to the rankings (if any) would be made if the weights of the measures were varied. If the fundamental objectives were found to be sensitive in this manner then sensitivity analysis would be conducted on the means objectives to see exactly which measures are the most sensitive to changes in the values for the measure's weight.

4.3.3.1 Sensitivity Analysis of Facility Impact Objective at Central AFB

Figure 4.9 shows that the triple paned low-e window with 1/2" argon gap and vinyl frame is the best alternative for almost all variances in the weight on the Facility Impact objective. It is not until the weight is lowered from its current value of 29.2% to 12% that the Triple paned window with low-e film, 1/2" air gap and vinyl frame is the top choice. Therefore this measure is fairly insensitive to changes in weighting.

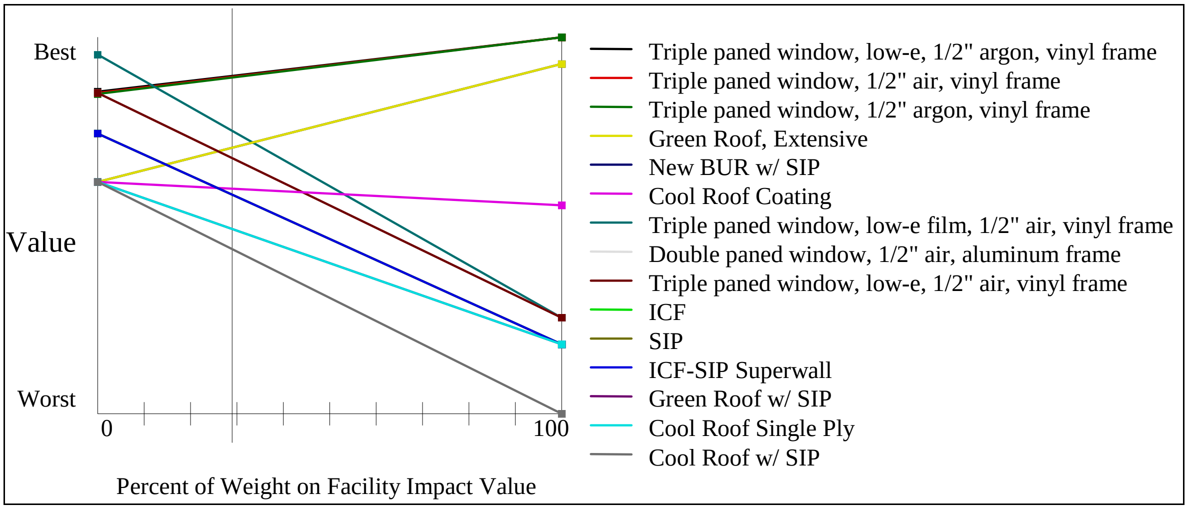

Figure 4.9: Sensitivity Analysis of Facility Impact Objective at Central AFB

4.3.3.2 Sensitivity Analysis of Facility Safety Improvements Objective at Central AFB

Figure 4.10 shows that the triple paned low-e windows with 1/2" argon gap and vinyl frames remain the best alternative until the weighting on facility safety impact is increased from its current value of 16.2% to approximately 38%, when the triple paned windows with low-e film become the best alternative. This is because the windows with low-e film provide additional blast protection. As more weight is placed on this measure, eventually the IFC-SIP Superwall becomes the best alternative (at 75%), because of the additional fire and blast protection this wall provides in addition to its energy savings. Overall, this measure is insensitive to changes in weighting, as an increase of 20% in the weighting of this measure is unlikely.

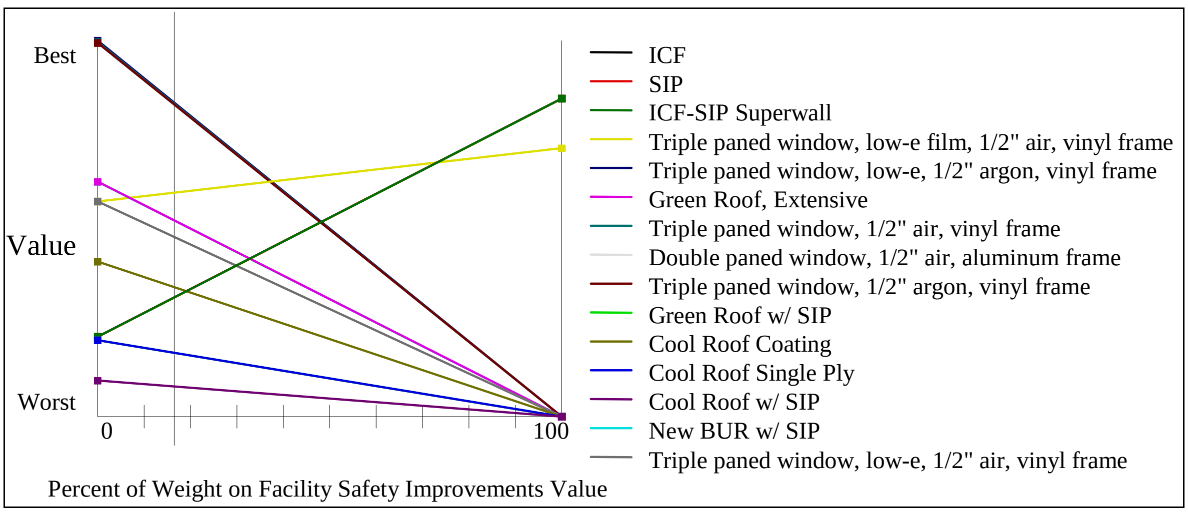

Figure 4.10: Sensitivity Analysis of Facility Safety Improvements Objective at Central AFB

4.3.3.3 Sensitivity Analysis of Resources Objective at Central AFB

This is also an insensitive measure, since the top alternative remains the best despite any changes to the weight of this measure. Figure 4.11 displays the sensitivity analysis for the resources objective.

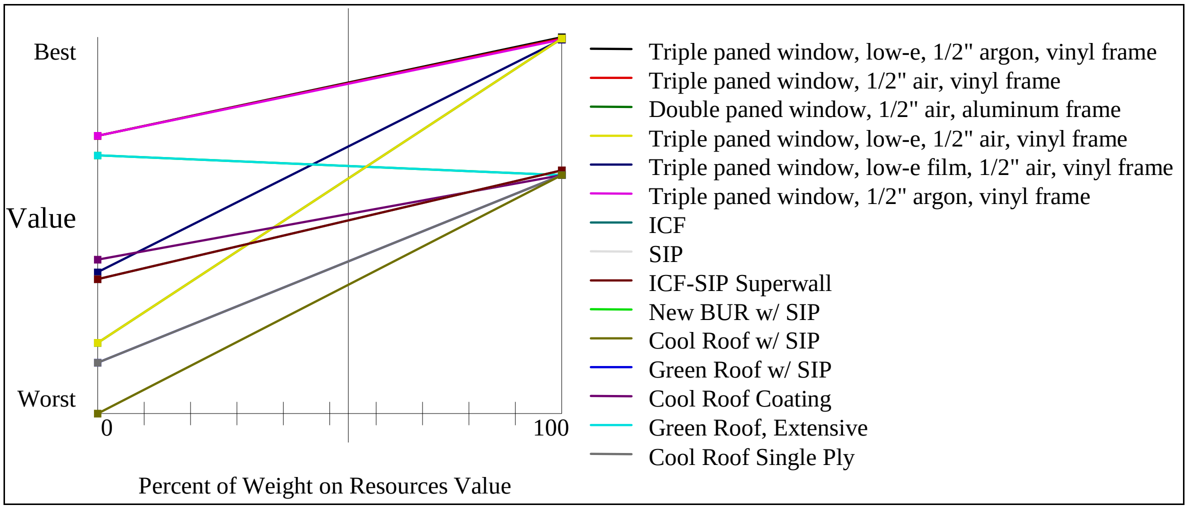

Figure 4.11: Sensitivity Analysis of Resources Objective at Central AFB

Each of the fundamental objectives were found to be insensitive to changes in the decision maker's weighting, therefore no further analysis is required.

4.4 Northeast AFB

4.4.1 Alternative Scoring of Northeast AFB

Northeast AFB is located in Dover, Delaware. The average annual temperature in Dover is 54.2 °F. The average annual percentage of possible sunshine at this location is 56% (Northeast Regional Climate Center, 2006). Table 4.2 shows the final data for the alternatives at Central AFB. More details about this data can be found in Appendix A.

Table 4.3: Building and Energy Data for Alternatives at Northeast AFB

Alternative	"SAVINGS RATIO"	Aesthetics	Blast Protection	Fire Rating	Building Component % Lifespan	Difficulty of Installation	Service Availability
Green Roof (Extensive)	0.05	1	no	no	19	3	local
Green Roof w/ SIP	0.05	1	no	yes	19	3	local
Cool Roof (Coating)	0.00	2	no	no	19	1	local
Cool Roof (Single Ply)	0.00	1	no	no	19	3	local
Cool Roof w/ SIP	0.04	2	no	yes	19	3	local
New BUR w/ SIP	0.04	1	no	yes	19	3	local
Triple paned windows, Low-e, 1/2" air, vinyl frame	2.37	2	no	no	95	2	local
Triple paned windows, 1/2" argon, vinyl frame	1.77	2	no	no	95	2	local
Triple paned windows, Low-e, 1/2" argon, vinyl frame	2.58	3	no	no	95	2	local
Triple paned windows, Low-e film, 1/2" air, vinyl frame	2.29	1	yes	no	95	2	local
Double paned windows, 1/2" air, aluminum frame w/ break	2.50	2	no	no	95	2	local
Triple paned windows, 1/2" air, vinyl frame	2.58	3	no	no	95	2	local
ICF	0.09	2	yes	yes	20	3	local
SIP	0.05	2	no	yes	20	3	local
SIP & ICF	0.06	2	yes	yes	20	3	local

Figure 4.12 shows that the triple paned window with low-e film, 1/2" air

gap and vinyl frame is the best alternative for this facility at Northeast AFB, followed very closely by the other five window technologies. The wall and roof technologies did not score nearly as high in any measure.

Alternative	Value
Triple paned, Low-e film, 1/2" air, vinyl	0.975
Triple paned, 1/2" air, vinyl	0.916
Triple paned, Low-e, 1/2" argon, vinyl	0.916
Double paned, 1/2" air, aluminum w/ break	0.914
Triple paned, Low-e, 1/2" air, vinyl	0.910
Triple paned, 1/2" argon, vinyl	0.890
ICF	0.276
ICF-SIP Superwall	0.259
Cool Roof Coating	0.204
Green Roof w/ SIP	0.185
SIP	0.185
Green Roof, Extensive	0.182
Cool Roof Single Ply w/ SIP	0.180
New BUR w/ SIP	0.180
Cool Roof Single Ply	0.153

Figure 4.12: Alternative scoring at Northeast AFB

4.4.2 Deterministic Analysis of Northeast AFB

All of the window technologies had very high scores in the savings ratio measure (all above 1.75), which was also weighted very high by the decision maker (32.2%). The windows also had a high score in the building component percent of useful life (95%), which was also weighted fairly high by the decision maker (20.3%). Figure 4.13 shows how the high scores and weights in these two measures allow the window technologies to dominate over the roof and wall technologies at Northeast AFB.

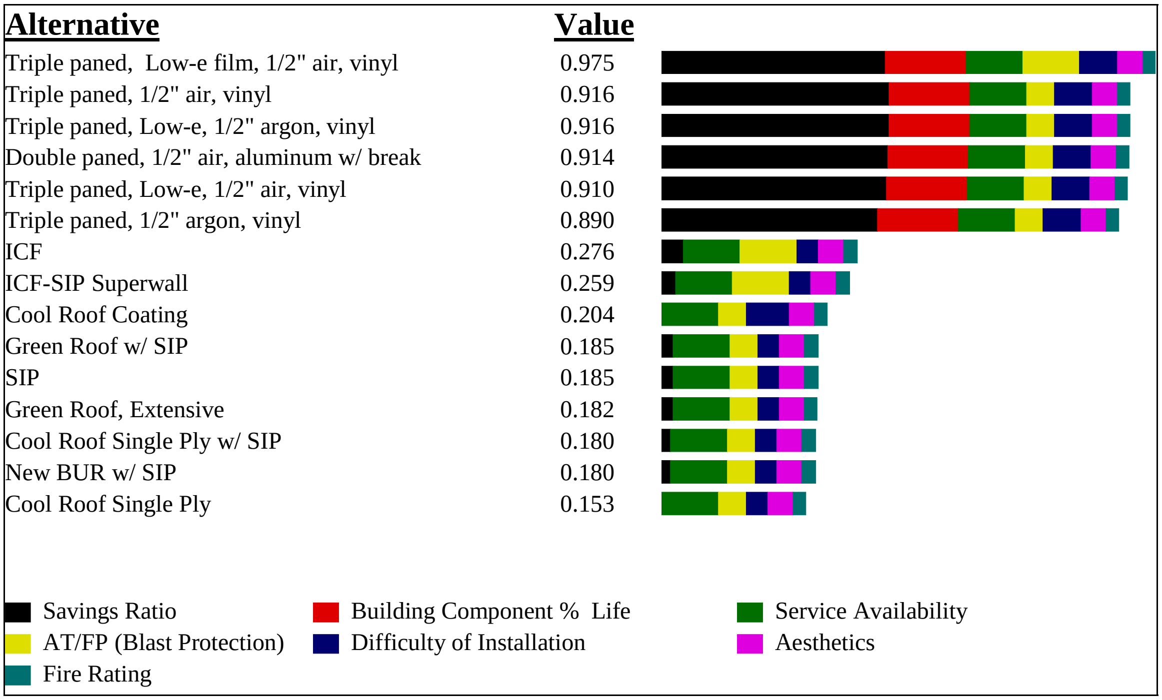

Figure 4.13: Alternative scores displayed with weighted SDVFs for Northeast AFB

Another insight to the model is comparing the actual weights of the measures to their effective weights. Figure 4.14 shows that the measure aesthetics and service availability both have an effective weight of zero. More importantly, it shows that the savings ratio measure has an effective weight of 63.2% and the building component percent of useful life measure has an effective weight of 22.4%. Combined, these two measures have an effective weight of 85.6%, and this explains why these two measures dominate the model overall.

Measure	Percentage Weight	Effective Weight
AT/FP (Blast Protection)	13.6	8.028
Aesthetics	6.8	0.000
Building Component % of Useful	20.3	22.397
Difficulty of Installation	10.2	6.021
Fire Rating	3.4	0.401
Savings Ratio	32.2	63.153
Service Availability	13.6	0.000

Figure 4.14: Actual and effective weights for means objectives at Northeast AFB

4.4.3 Sensitivity Analysis of Northeast AFB

As in the previous sections, sensitivity analysis was first performed on the fundamental objectives to determine what changes to the rankings (if any) would be made if the weights of the measures were varied. If the fundamental objectives were found to be sensitive in this manner then sensitivity analysis would be conducted on the means objectives to see exactly which measures are the most sensitive to changes in the values for the measure's weight.

4.4.3.1 Sensitivity Analysis of Facility Impact Objective at Northeast AFB

The facility impact objective was found to be insensitive to changes in this measures weight, as the triple paned window with low-e film, 1/2" air gap and vinyl frames is the best alternative unless the weight is increased from its current value of 17% to 91%. At that point the cool roof coating becomes the best alternative.

Since such a dramatic increase in the weight of this objective is unlikely, this objective is insensitive to changes in weighting.

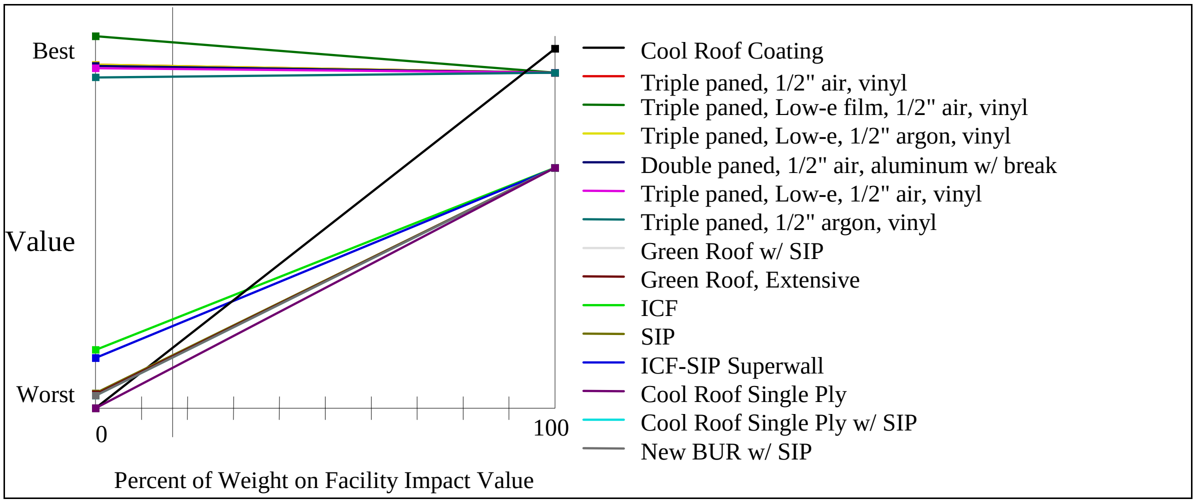

Figure 4.15: Sensitivity Analysis on Facility Impact Objective at Northeast AFB

The facility safety improvements objective was also found to be insensitive, as the best alternative remains the top choice unless the weight on this objective is increased from its current value of 17% to 99%. At this point the ICF-SIP Superwall would become the best alternative because of its additional fire and blast protection.

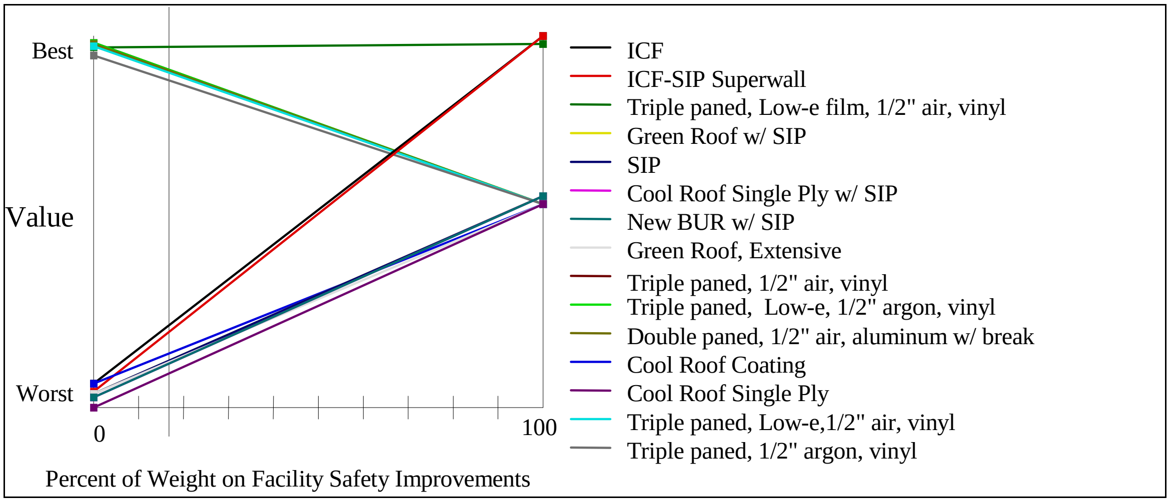

Figure 4.16: Sensitivity Analysis on Facility Safety Improvements Objective at Northeast AFB

Lastly, the resources objective was found to be insensitive to changes in weighting, as the weight of this measure would have to be increased from its current value of 66% to 90% in order for the best alternative to change from the triple paned window with low-e film, 1/2" air gap and vinyl frames to the triple paned window with 1/2"argon gap and vinyl frame.

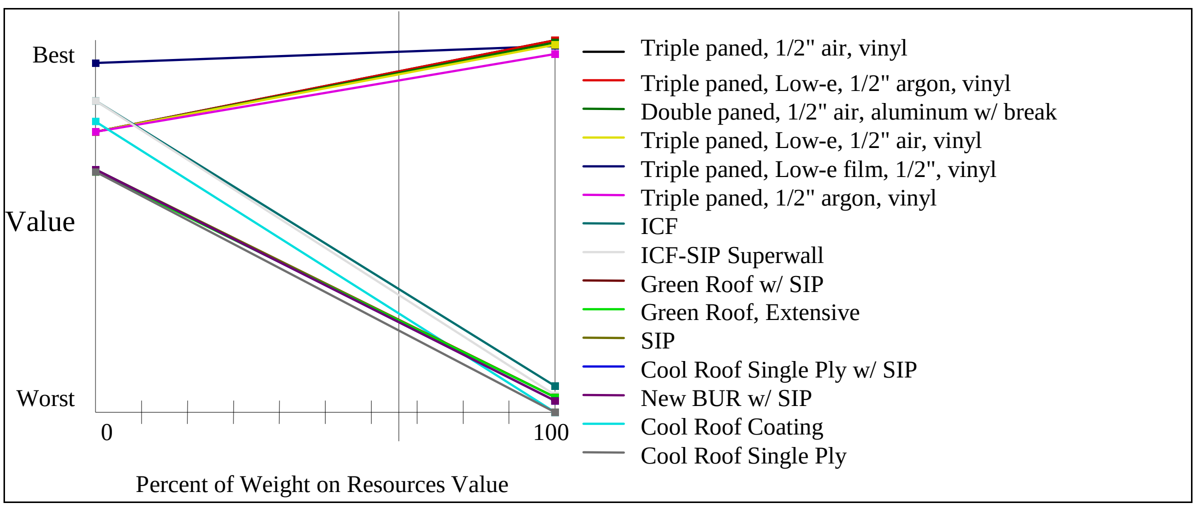

Figure 4.17: Sensitivity Analysis on Resources Objective at Northeast AFB

Each of the fundamental objectives were found to be insensitive to changes in the decision maker’s weighting, therefore no further analysis is required.

V. Summary and Conclusions

5.1 Overview

This chapter will discuss the last step in Shoviak's Ten Step VFT Process. First, a summary of the research will be presented, and each of the research questions from Chapter 1 will be addressed. Then a summary of the value model strengths will be presented followed by some of the limitations of the value model. Lastly, this chapter will recommend areas for future research and present the final conclusions of this research.

5.2 Research Summary

This research provides a tool that DoD decision makers can use to determine the practicality of retrofitting a certain facility with an energy efficient building envelope technology. The research also determined what Air Force Civil Engineer Operations Flight Chiefs found to be of value in this difficult decision. The value model that was developed was made to be adaptable at any climate and location, to fit any type of facility, and to be used by any DoD decision maker.

5.3 Research Questions

Four research questions were asked as the basis for this research endeavor. Listed below is each question with its respective answer.

1. What energy saving building envelope retrofit technologies are available for use and where have they been used successfully?

There are numerous building envelope technologies that are currently available in the commercial world that can be used to retrofit DoD facilities. There are hundreds of variations of window and glazing technologies, including variations on multiple panes, size of gap between panes, type of gas in that gap, low-emissivity films, and different frame types such as fiberglass and vinyl. Wall technologies include structural insulating panels (SIPs) and insulating concrete forms (ICFs), and they can be combined to create a very strong and energy efficient ICF-SIP Superwall. Roof technologies include cool roofs and green roofs, and there are multiple types of each kind including single ply cool roofs, cool roof coatings, and extensive or intensive green roofs. There are numerous manufacturers and contractors that develop and install each of these various building envelope technologies, and while each manufacturer is different, the basic properties of these technologies remains the same.

2. What do decision makers in the Department of Defense value in terms of building envelope performance and indoor air quality (IAQ)?

The decision makers chosen to use for this research were those most likely to make retrofit decisions on an Air Force installation. That person would normally be the Civil Engineer Operations (Ops) Flight Chief. After discussions with numerous Ops Flight Chiefs, it was found that the one measure they all seem to value most was the savings ratio. Most Ops Flight Chiefs were very happy if they could receive at least a ratio of 1, meaning the technology would pay itself off within 10 years. Anything beyond that was extra justification for installing the technology. The decision makers also valued the aesthetics of the technology, availability of maintenance personnel to service the technology, difficulty of installation of the technology, and additional safety features of the technology such as additional blast and fire protection. Lastly, decision makers valued the lifespan of the component they were considering for replacement. They did not put much value into a component that was relatively new, they would rather replace a component that had already lived its useful life and needed to be replaced. Retrofitting facilities with these building envelope technologies would have little, if any, impact on indoor air quality. If there were any impact, the facility's mechanical system would have to make up for the difference in ventilation to the indoor space. Therefore any impact to IAQ was not considered in this research.

3. How much energy will be saved by incorporating these energy saving building envelope retrofit technologies?

In the three climates simulated, the window technologies were found to save the most energy. The window technologies were found to save between 10-17% of cooling energy (kWh) in all three climates, and between 42-94% of heating energy (BTUs) in all three climates. The low-e windows tended to save more energy in cooling, while the better insulating windows with the argon gas in the gap tended to save more energy in heating. Surprisingly, the double paned windows with 1/2" air gap and aluminum frames had quite a bit of energy savings over the single paned frames that were simulated, but the energy savings gained was about half of the other five window technologies simulated. See Appendix A for complete details of energy savings at each location.

Cool roofs saved quite a bit of cooling energy at Southwest AFB (between 14-16%) but had a heating energy penalty as the literature predicted (-24%). Since cooling energy dominated at this climate, the overall energy savings was about 7.5%. The cooling energy saved at Central AFB was much less (1-2%) and the penalty in heating energy took away any savings in cooling energy. Cool roofs at Northeast AFB performed in the same manner as Central AFB. The cool roof coating had very similar energy savings to the single ply cool roof, and the single ply cool roof with additional SIP saved a little more energy due to its insulating properties, negating the heating penalty associated with cool roofs. Therefore a single ply cool roof with an SIP had the highest overall energy savings at Southwest AFB, however, just adding an SIP to a new built up roof had the same effect as a cool roof with an SIP in the Central and Northeast climates.

Green Roofs were found to have about half of the energy savings in cooling as cool roofs (7% at Southwest AFB and Northeast, 1% at Central AFB), but their insulating properties allowed them to also have the additional benefit of heating energy savings (17-38% at Southwest AFB, 30% at Central AFB, 10-17% at Northeast AFB). The green roof with the additional SIP installed had greater insulating properties therefore had additional heating energy savings at all locations.

Both wall technologies had very small energy savings, both heating and cooling. At Southwest AFB, all three wall technologies had a cooling energy savings of 0.4-0.8%, and a heating energy savings of 12-19%. At Central AFB the cooling energy saved was from 4-7% and the heating energy saved was from 7-11%. Lastly at Northwest AFB the cooling energy saved was 0.1-0.4% and the heating energy saved had a range of 2-8%.

The energy savings for each of these technologies is in line with the percentage of energy that is typically transferred through each component (See Figure 2.3). If 50% of the energy being transferred through the building envelope is transferred through the windows, it makes sense that the window technologies have the ability to save the most energy. Likewise, if only 16% of that energy transfers through the roof and 10% through the walls, there is less total energy available to save for the roof and wall technologies. Also, the roof technologies will save more energy than the wall technologies simply because of its greater surface area with a higher angle of incidence towards the sun.

4. *What is the most appropriate policy vehicle to incorporate these technologies into existing buildings?*

The most appropriate policy vehicle to incorporate these technologies into existing DoD buildings would be through the Energy Conservation Investment Program (ECIP) and Energy Savings Performance Contracts (ESPC). These are contracts specifically designed for energy conserving projects such as retrofitting existing buildings with these technologies. By using these contracts, there are no upfront costs to the government. The project costs are paid by an Energy Service Company (ESCO), and the ESCO is then repaid through guaranteed energy savings

5.4 Value Model Strengths

The main strength of this model is that it established what DoD decision makers value in terms of retrofitting existing facilities with these new building envelope technologies. The model that was developed in this research is an objective mathematical model that limits the usual biases in this decision. The model was also developed to be used by any DoD decision maker for any facility at any climate. Additionally, any other building envelope technologies not presented in this research can be input into the model. The model is also very flexible, and allows the decision maker to see the exact strengths and weaknesses of each technology, as well as to conduct sensitivity analysis to determine if their initial assumptions were correct.

5.5 Limitations

This model is based on several assumptions. First, the energy simulations were based on a generic office building. The facility was designed in EQuest as simply as possible, and complex facilities may have different energy estimates. For example, these building envelope technologies may perform better or worse with various HVAC systems or in a different type of facility such as a warehouse or industrial facility.

Although the model was developed through discussions with AFCESA building envelope experts and Air Force decision makers, the model could also be improved after further discussions with more experts and decision makers throughout DoD. Some measures not previously thought of, such as additional public relations benefits due to installing these energy efficient technologies may be of some value to the model.

5.6 Areas for Future Research

Future research should focus on how these energy saving technologies will work in a variety of building types, such as industrial facilities and warehouses. Also, it would be interesting to see how these technologies work with various HVAC systems, such as systems with intermittent fans and variable air volume systems. An analysis of how these technologies would perform in new construction would be of interest to the Air Force and the Department of Defense. Lastly, research should focus on how "tightening" the building envelope can affect indoor air quality, and also how these new building envelope technologies can help combat the urban heat island effect.

5.6 Final Conclusions

This research has shown not only that value focused thinking is an appropriate methodology for selecting energy efficient building envelope technologies to retrofit into existing DoD facilities, but that these technologies are capable of saving great deals of energy, which can reduce the United States dependence on foreign sources of energy as well as save the U.S. taxpayers millions of dollars per year. Since the energy savings from these technologies will more than pay for their installations and maintenance costs, they should always be considered for retrofit into any one of the Air Force's "average" facilities.

APPENDIX A: SUMMARY OF MEASURES

Measure: Aesthetics

Definition: How does the new building envelope technology affect the aesthetics of the building?

SDVF for Southwest AFB:

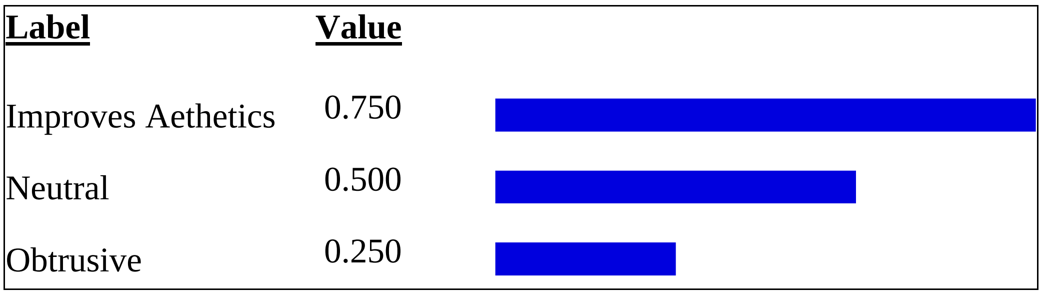

Figure A1: Aesthetics SDVF for Southwest AFB

SDVF for Central AFB:

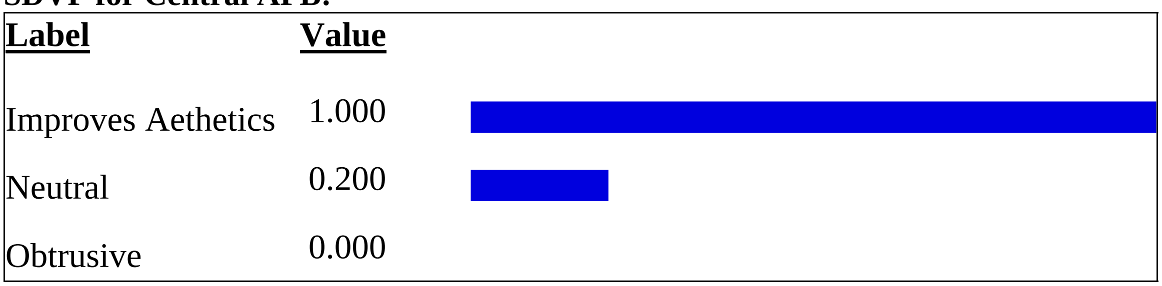

Figure A2: Aesthetics SDVF for Central AFB

SDVF for Northeast AFB:

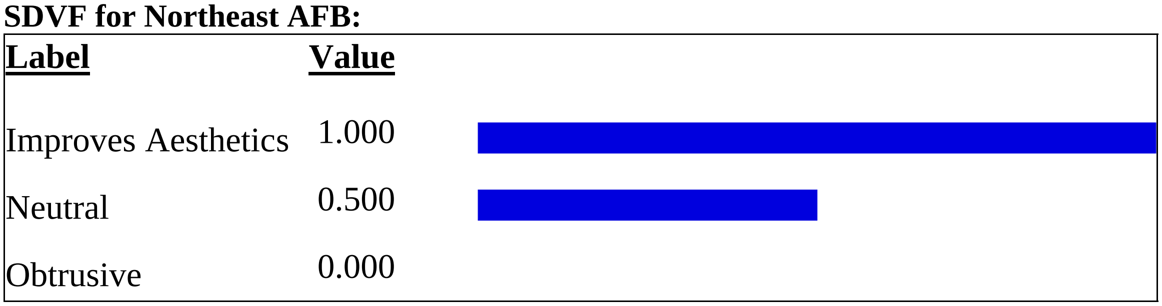

Figure A3: Aesthetics SDVF for Northeast AFB

Category Definitions:

Improves Aesthetics: The new building envelope technology is visibly appealing to the building occupants.
Neutral: The new building envelope technology is unnoticeable to building occupants.

Obtrusive: The new building envelope technology is visibly unappealing to building occupants.

Comments:

Values for this measure can only be obtained by interviewing the building occupants of the facility where the new building envelope technology is being installed. For this research the values were obtained using the Microsoft Excel random function.

Measure: Difficulty of Installation

Definition: The number of days it takes to install the new building envelope technology

SDVF for Southwest AFB:

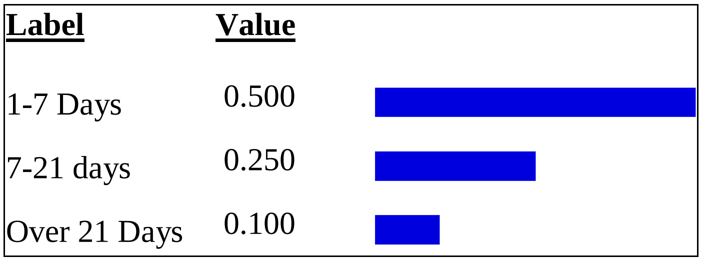

Figure A4: Difficulty of Installation SDVF for Southwest AFB

SDVF for Central AFB:

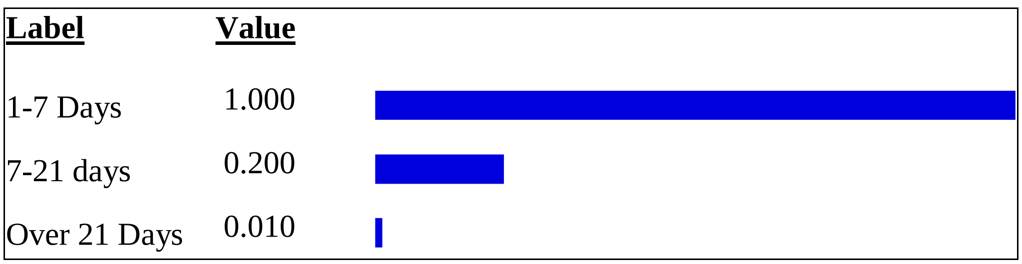

Figure A5: Difficulty of Installation SDVF for Central AFB

SDVF for Northeast AFB:

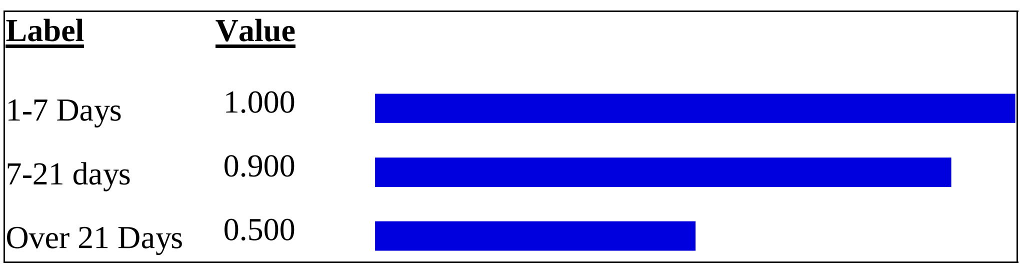

Figure A6: Difficulty of Installation SDVF for Northeast AFB

Category Definitions:

As shown in each SDVF.

Comments:

Installation time estimates were derived through a combination of local contractor estimates as well as a review of the current literature on each new building envelope technology.

Measure: AT/FP (Blast Protection)

Definition: Does the new building envelope technology improve the blast protection of the existing facility?

SDVF for Southwest AFB:

Label	Value
Improve Blast Protection	0.100
No Change to Blast	0.000

Figure A7: Blast Protection SDVF for Southwest AFB

SDVF for Central AFB:

Label	Value
Improve Blast Protection	0.850
No Change to Blast	0.400

Figure A8: Blast Protection SDVF for Central AFB

SDVF for Northeast AFB:

Label	Value
Improve Blast Protection	1.000
No Change to Blast Protection	0.500

Figure A9: Blast Protection SDVF for Northeast AFB

Category Definitions:

Improves blast protection: The new building envelope technology will improve the blast protection of the existing facility.

No change to blast protection: The new building envelope technology will not improve the blast protection of the existing technology.

Comments:

Information on blast protection properties was taken from a review of current literature on each technology. Only two technologies (ICFs and Windows with Low-e film) had any mention of having additional blast protection qualities.

Measure: Fire Rating

Definition: Does the new building envelope technology improve the fire rating of the existing facility?

SDVF for Southwest AFB:

Label	Value
Increase Fire Rating	0.100
No change in Fire Rating	0.000

Figure A10: Fire Rating SDVF for Southwest AFB

SDVF for Central AFB:

Label	Value
Increase Fire Rating	0.250
No change in Fire Rating	0.000

Figure A11: Fire Rating SDVF for Central AFB

SDVF for Northeast AFB:

Label	Value
Increase Fire Rating	1.000
No change in Fire Rating	0.900

Figure A12: Fire Rating SDVF for Northeast AFB

Category Definitions:

Increase fire rating: The new building envelope technology will increase the fire rating of the existing facility.

No change to blast protection: The new building envelope technology will not increase the fire rating of the existing technology.

Comments:

Information on fire rating properties was taken from a review of current literature on each technology. Only two technologies (ICFs and SIPs) had any mention of having an increased fire rating.

Measure: Building Component % of useful life

Definition: How long the existing building component under consideration for replacement has been in place in respect to its useful lifespan (0-100%). For example, a roof that has been in place 10 years out of its normal 20 year lifespan would have a score of 50%.

SDVF for Southwest AFB:

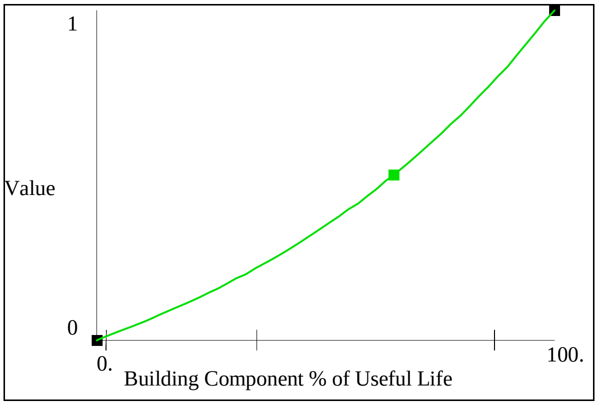

Figure A13: Building Component % of Useful Life SDVF for Southwest AFB

SDVF for Central AFB:

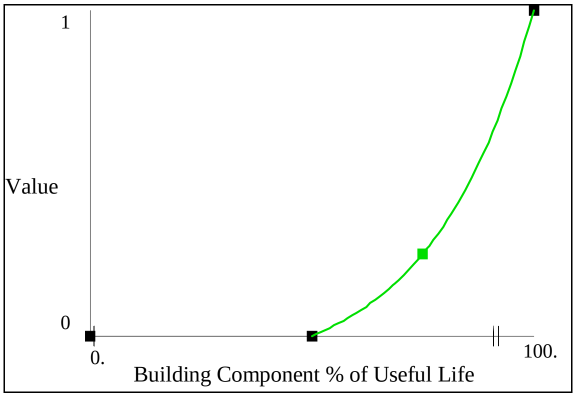

Figure A14: Building Component % of Useful Life SDVF for Central AFB

SDVF for Northeast AFB:

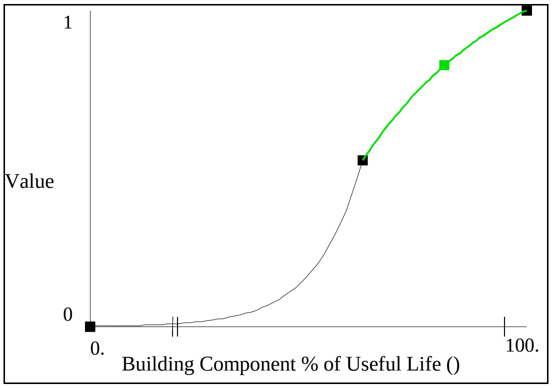

Figure A15: Building Component % of Useful Life SDVF for Northeast AFB

Comments:

This value is facility dependent. Scores used in this research were obtained using the Microsoft Excel random function.

Measure: Savings Ratio

Definition: Energy Savings ($) per Installation/Maintenance Costs (Present Value, $)

SDVF for Southwest AFB:

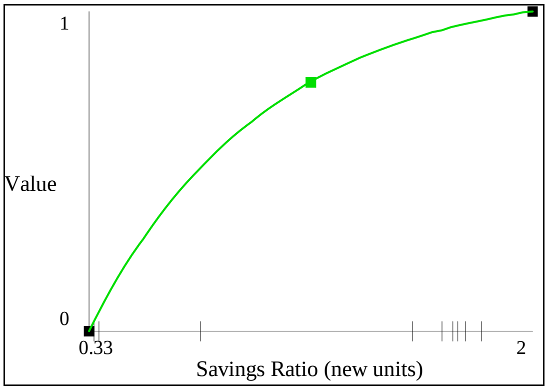

Figure A16: Savings Ratio SDVF for Southwest AFB

SDVF for Central AFB:

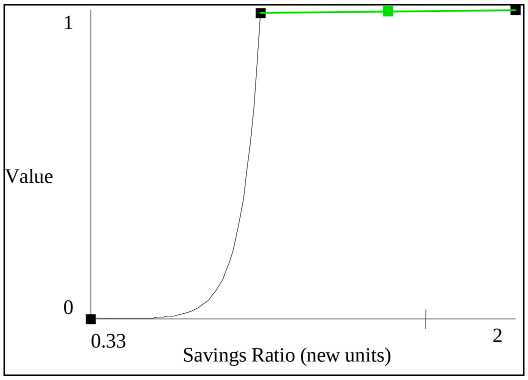

Figure A17: Savings Ratio SDVF for Central AFB

SDVF for Northeast AFB:

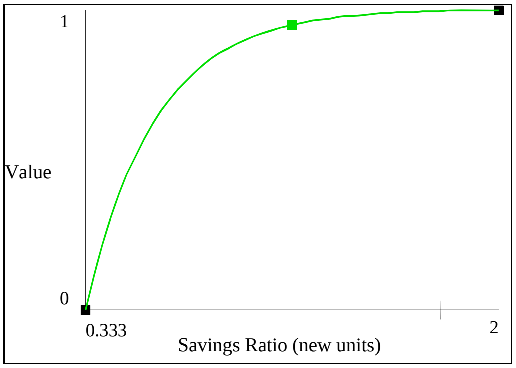

Figure A18: Savings Ratio SDVF for Northeast AFB

Comments:

Installation and Maintenance costs were provided by a combination of local contractor estimates as well as a review of the current literature on each building envelope technology. Energy savings (kWh for cooling and BTUSs for heating) were calculated using the EQuest energy simulation software, and multiplied by \$0.0906/kwh and \$1.092/therm (Federal Register, 2005) to estimate energy savings in dollars (BTUSs were converted to therms for ease of calculations). The savings ratio measure was governed by the equations 3.1 (CFR, 2000b) and 3.2 (Turner, 2001:45). Tables A1-A3 display the energy and cost data for each location.

$$\text{Savings Ratio} = \frac{\text{Present Value(Energy Savings)}}{\text{Installation Costs} + \text{Present Value(Maintenance Costs)}} \qquad (3.1)$$

Where:

$$\text{Present Value(FV)} = \sum_{n=\text{year costs occur}} (FV)(1+i)^{-n} \qquad (3.2)$$

Where:

PV = Present Value (\$)

FV = Future value of maintenance cost or energy savings (\$)

i = rate of inflation (decimal, assumed to be 0.0349 (Inflation Data, 2006)

n = year of annual cost or savings

Table A1: Energy and Cost Data for Southwest AFB

Alternative	DOE-2 Simulated Electricity Used (kWh	DOE-2 Simulated Gas Used (BTUS to therm)	Annual Energy "Saved" (kWh)	Annual Energy "Saved" (BTUS to therm)	Annual Energy Saved ($$) (Assume 0.09/kwh and 1.09/therm)	% of Cooling Energy Saved	% of Heating Energy Saved	Installation Cost	Annual Maintenance Cost
Baseline	294050	305.7	0	0	$0.00	0.00%	0.00%	$0.00	$18,750*
Green Roof (Extensive)	284220	297.5	9830	8.2	$893.64	6.93%	17.72%	$187,500.00	$25,000.00**
Green Roof w/ SIP	283820	287.3	10230	18.4	$940.76	7.20%	37.80%	$205,000.00	$25,000.00**
Cool Roof (Coating)	273020	318.7	21030	-13	$1,878.53	14.24%	-24.02%	$12,500.00	$12,500.00*
Cool Roof (Single Ply)	272840	318.3	21210	-12.6	$1,895.17	14.36%	-23.23%	$37,500.00	$18,750.00*
Cool Roof w/ SIP	269440	298.7	24610	7	$2,222.53	16.64%	15.16%	$55,000.00	$18,750.00*
New BUR w/ SIP	293810	292.9	240	12.8	$35.55	0.16%	25.00%	$42,500.00	$18,750.00*
Triple paned Low-e Window 1/2" air gap, vinyl frame	271270	259.4	22780	46.3	$2,100.67	15.24%	91.14%	$16,800.00	$0.00
Triple paned window 1/2" argon gap, vinyl frame	269250	259.4	24800	46.3	$2,282.47	16.94%	92.72%	$19,200.00	$0.00
Triple paned window, Low-e w/ 1/2" argon gap, vinyl frame	271540	258.4	22510	47.3	$2,077.46	15.06%	93.11%	$16,000.00	$0.00
Triple paned window, Low-e film 1/2" air gap, vinyl frame	270550	260	23500	45.7	$2,164.81	15.73%	89.96%	$17,600.00	$0.00
Double paned window, 1/2" air gap aluminum frame	281550	263.4	12500	42.3	$1,171.11	8.36%	83.07%	$9,600.00	$0.00
Triple paned window, 1/2" air gap vinyl frame	278860	258.3	15190	47.4	$1,418.77	10.16%	93.31%	$12,800.00	$0.00
ICF	293210	299.5	840	6.2	$82.36	0.56%	12.01%	$34,500.00	$0.00
SIP	293410	298.5	640	7.2	$65.45	0.43%	13.98%	$30,000.00	$0.00
SIP & ICF Wall	292860	296.1	1190	9.6	$117.56	0.80%	18.70%	$64,500.00	$0.00

* Maintenance is required every 10 years (EPA, 2006)

** Maintenance is only required for the first two years (U W-Milwaukee, 2006)

Table A2: Energy and Cost Data for Central AFB

Alternative	DOE-2 Simulated Electricity Used (kWh)	DOE-2 Simulated Gas Used (BTUS to therm)	Annual Energy "Saved" (kWh)	Annual Energy "Saved" (BTUS to therm)	Annual Energy Saved ($$) (Assume 0.09/kwh and 1.092/therm)	% of Cooling Energy Saved	% of Heating Energy Saved	Installation Cost (* sq ft)	Annual Maintenance Cost
Baseline	208500	3169.5	0	0	$0.00	0.00%	0.00%	$0.00	$18,750.00*
Green Roof (Extensive)	207790	3149.2	710	20.3	$86.03	1.13%	0.72%	$187,500.00	$25,000.00**
Green Roof w/ SIP	208230	2887.6	270	281.9	$331.57	0.43%	10.00%	$205,000.00	$25,000.00**
Cool Roof (Coating)	207400	3243.8	1100	-74.3	$18.01	1.75%	-2.63%	$12,500.00	$12,500.00*
Cool Roof (Single Ply)	207840	3211.4	660	-41.9	$13.73	1.06%	-1.49%	$37,500.00	$18,750.00*
Cool Roof w/ SIP	208190	2897.8	310	271.7	$324.05	0.50%	9.63%	$55,000.00	$18,750.00*
New BUR w/ SIP	208230	2895.7	270	273.8	$322.74	0.43%	9.71%	$42,500.00	$18,750.00*
Triple paned Low-e Window 1/2" air gap, vinyl frame	200840	974.3	7660	2195.2	$3,082.17	12.32%	77.83%	$16,800.00	$0.00
Triple paned window 1/2" argon gap, vinyl frame	204080	1139.6	4420	2029.9	$2,610.39	7.11%	71.97%	$19,200.00	$0.00
Triple paned window, Low-e w/ 1/2" argon gap, vinyl frame	195630	966.6	12870	2202.9	$3,559.46	15.35%	78.10%	$16,000.00	$0.00
Triple paned window, Low-e film 1/2" air gap, vinyl frame	200440	1094.6	8060	2074.9	$2,987.04	12.97%	73.56%	$17,600.00	$0.00
Double paned window, 1/2" air gap aluminum frame	204290	1853.8	4210	1315.7	$1,813.01	6.77%	46.61%	$9,600.00	$0.00
Triple paned window, 1/2" air gap vinyl frame	204330	1228.6	4170	1940.9	$2,490.88	6.69%	68.81%	$12,800.00	$0.00
ICF	205430	2623.1	3070	546.4	$871.88	4.94%	7.00%	$34,500.00	$0.00
SIP	205560	2961.3	2940	208.2	$491.54	4.73%	7.38%	$30,000.00	$0.00
SIP & ICF Wall	204580	2521.6	3920	647.9	$1,059.01	6.31%	10.60%	$64,500.00	$0.00

Table A3: Energy and Cost Data for Northeast AFB

Alternative	DOE-2 Simulated Electricity Used (kWh)	DOE-2 Simulated Gas Used (BTUS to therm)	Annual Energy "Saved" (kWh)	Annual Energy "Saved" (BTUS to therm)	Annual Energy Saved ($$) (Assume 0.09/kwh and 1.09/therm)	% of Cooling Energy Saved	% of Heating Energy Saved	Installation Cost (* sq ft)	Annual Maintenance Cost
Baseline	216940	3273.7	0	0	$0.00	0.00%	0.00%	$0.00	$18,750.00*
Green Roof (Extensive)	212060	2967.3	4880	306.4	$773.18	7.63%	10.44%	$187,500.00	$25,000.00**
Green Roof w/ SIP	212270	2783.5	4670	490.2	$954.62	7.34%	16.69%	$205,000.00	$25,000.00**
Cool Roof (Coating)	216830	3278.3	110	-4.6	$4.89	0.16%	-0.16%	$12,500.00	$12,500.00*
Cool Roof (Single Ply)	216850	3274.3	90	-0.6	$7.45	0.13%	-0.02%	$37,500.00	$18,750.00*
Cool Roof w/ SIP	216960	3061.8	-20	211.9	$229.17	-0.03%	7.20%	$55,000.00	$18,750.00*
New BUR w/ SIP	216950	3063.1	-10	210.6	$228.65	-0.01%	7.15%	$42,500.00	$18,750.00*
Triple paned Low-e Window 1/2" air gap, vinyl frame	209540	1272.4	7400	2001.3	$2,847.42	10.44%	67.98%	$16,800.00	$0.00
Triple paned window 1/2" argon gap, vinyl frame	213120	1359.2	3820	1914.5	$2,430.61	5.39%	65.03%	$19,200.00	$0.00
Triple paned window, Low-e w/ 1/2" argon gap, vinyl frame	210040	1133.1	6900	2140.6	$2,954.25	9.74%	72.72%	$16,000.00	$0.00
Triple paned window, Low-e film 1/2" air gap, vinyl frame	209050	1295.2	7890	1978.5	$2,866.67	11.13%	67.21%	$17,600.00	$0.00
Double paned window, 1/2" air gap aluminum frame	212900	2034.4	4040	1239.3	$1,714.44	5.70%	41.99%	$9,600.00	$0.00
Triple paned window, 1/2" air gap vinyl frame	212780	1447.3	4160	1826.4	$2,365.18	5.87%	62.04%	$12,800.00	$0.00
ICF	216170	3132.1	770	141.6	$223.64	0.34%	4.81%	$34,500.00	$0.00
SIP	216850	3189.2	90	84.5	$100.21	0.13%	2.87%	$30,000.00	$0.00
SIP & ICF Wall	216650	3058.7	290	215	$260.45	0.41%	7.30%	$64,500.00	$0.00

Measure: Service Availability

Definition: Whether maintenance personnel are available in the local area to service the new building envelope technology

SDVF for Southwest AFB:

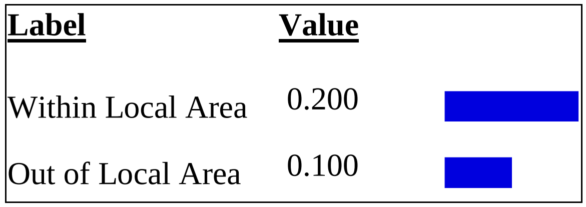

Figure A19: Service Availability SDVF for Southwest AFB

SDVF for Central AFB:

Figure A20: Service Availability SDVF for Central AFB

SDVF for Northeast AFB:

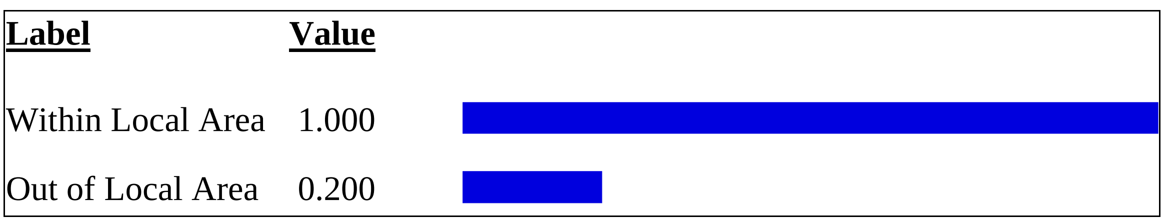

Figure A21: Service Availability SDVF for Northeast AFB

Category Definitions:

Within the local area is defined as within 100 miles of the base.

Out of local area is defined as over 100 miles away from the base.

Comments: Scores were obtained by searching for contractors within the local area of each of the respective bases for each building envelope technology.

APPENDIX B: DETAILS OF GENERIC FACILITY

Office Building
2-Story (2 floors above grade)
25,000 sq ft
Oriented North
Floor to Floor height: 12 ft
Floor to Ceiling height: 9 ft

Roof Construction:
Metal frame, > 24 in o.c.
3-ply built up roof (BUR)
Gravel finish
3 in polysocyanurate (R-21) insulation

Wall construction:
Metal frame, 2x6, 24 in o.c.
Brick exterior
Batt insulation (R-19)
Additional 1 in polyurethane (R-6) insulation

Windows:
Single pane, 1/8”
Aluminum frame w/ thermal break
4 windows per side, 53.3% of total wall area

Schedule:
7 am – 5 pm M-F, no weekends or holidays
HVAC starts one hour before and stops one hour after scheduled duty hours

HVAC:
Packaged Single Zone Direct Expansion (DX) with furnace 11.25-20 ton
Minimum 0.5 cfm/sq ft
Continuous Fan

Setpoints:
Occupied: Cool: 76 °F Heat: 70 °F
Unoccupied: Cool: 82 °F Heat: 64 °F

Details of simulating new building envelope technologies in EQuest:

EQuest only has “typical” building envelope components in its simulation library, so in order to simulate the new building envelope technologies some assumptions were necessary.

Green Roof:
Layered typical BUR with gravel and soil, assumed R-value of R-34 (average R-value of Green Roof based on literature review).

Cool Roof (Coating):
Same BUR as Baseline facility, changed absorbance to 0.25 (meaning reflectivity of 0.75, typical of a cool roof coating based on literature review).

Cool Roof (single ply):
Added another layer to the Baseline BUR (making it 4-ply) and changed absorbance of 0.25.

Green Roof/Cool Roof/New BUR with SIP
Added an SIP layer under the roofing layers. R-value for SIP was R-28 (based on literature review and local contractor estimates).

Windows:
This was the only technology that I could specifically select in EQuest. Each window/frame combination was available in the EQuest simulation library.

ICF:
Added extra layers of polystyrene and concrete to form ICF wall, R-value was R-30 (based on literature review and estimates from local contractors).

SIP:
Added extra layers of plywood and polystyrene to form SIP wall, R-value was R-28 (based on literature review and local contractor estimates).

ICF-SIP Superwall:
Combined the ICF and SIP wall layers. R-value was combined R-58.

BIBLIOGRAPHY

Air Force Civil Engineer Support Agency. "AFIT Student Help." Electronic Message. 15 Nov 2005a.

-----. "ECIP defined." 2005b. http://www.afcesa.af.mil/ces/cesm/energy/documents/ECIPDefined.pdf

Akbari, Hashem and Bretz, Sarah. "Cool Systems for Hot Cities." *Professional Roofing*, October 1998.

Arvai, J.L., Gregory, R. and McDaniels T.L. "Testing a structured decision approach: value-focused thinking for deliberative risk communication." Risk Analysis. Vol 21, Issue 6. 2001.

American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) *Handbook – Fundamentals*. Atlanta, 1997.

Bush, George H. W. *Energy Policy Act of 1992 (EPact).* Subtitle F of P.L. 102-486, Federal Agency Energy Management 1992. http://www.eere.energy.gov/femp/pdfs/epact92_f.pdf

Bush, George W. *National Energy Policy*. 2001. http://www.whitehouse.gov/energy/National-Energy-Policy.pdf

Carter, Jimmy. "The President's Proposed Energy Policy." 18 April 1977. *Vital Speeches of the Day*, Vol. XXXXIII, No. 14, May 1, 1977, pp. 418-420.

Clemen, Robert T. and Reilly, Terence. *Making Hard Decisions with DecisionTools®,* Duxbury Press, Belmont, CA, 2001.

Clinton, William J. *Executive Order 13123--Greening the Government Through Efficient Energy Management.* Federal Register page and date: 64 CFR 109: 30851-30860, 8 June 1999. http://www.nara.gov/fedreg/eo.html

Code of Federal Regulations. *Energy Conservation Voluntary Performance Standards for New Buildings; Mandatory for Federal Buildings.* Title 10 Part 435. 2000a. http://www.access.gpo.gov/nara/cfr/waisidx_00/10cfr435_00.html

-----. *Savings to Investment Ratio.* Title 10 Part 436 Section 21. 2000b. http://www.access.gpo.gov/nara/cfr/waisidx_00/10cfr436_00.html

Department of Energy. "Landscaping for Energy Efficiency." DOE/GO-10095-046. FS 220. April,1995.

-----. "Building Envelope Components." 2005a. http://www.eere.energy.gov/buildings/info/components/envelope/

-----. "Building Envelope Technologies." 2005b. http://www.eere.energy.gov/EE/buildings_envelope.html

-----. "Indoor Air Quality Research and Development." 2005c. http://www.eere.energy.gov/buildings/tech/indoorairquality.html

-----. "New Construction/Retrofits." 2005d. http://www.eere.energy.gov/femp/program/newconstruction.cfm

Dvorak, Bruce and de la Fleur, Marcus. "The Emerging Culture of Greenroof Technology." 2005. www.cdfinc.com/CDF_Resources/Emerging%20Culture%20of%20Green%20Roof%20Technology.pdf

Elder, Keith. "Building Envelope." *Energy User News*, Vol 25, Issue 11, November 2000. pg 32-34.

Energy Information Administration. "Environment: energy-related emissions data & environmental analyses." 2005. http://www.eia.doe.gov/environment.html

Energy Source Builder. "Insulation Values Uncovered." Issue 33, June 1994.

Environmental Protection Agency (EPA). "Cool Roof Product Information." 2006. http://www.epa.gov/heatisland/strategies/level3_roofproducts.html

Federal Energy Management Program (FEMP). "Spectrally Selective Glazings." DOE/EE-0173. August 1998.

-----. "Green Roofs." DOE/EE-0298. August 2004a.

-----. "Energy Efficient Roof Products." 2004b. http://www.eere.energy.gov/femp/technologies/eep_roof_products.cfm

Federal Register. "Representative Average Unit Costs of Energy." Vol 70, No 47. Mar 11, 2005.

Garman, David K. "Energy Efficiency Improvements in Federal Buildings and Vehicles" 2003. http://www1.eere.energy.gov/office_eere/congressional_test_0312_203.html

ICF Association. "Insulating Concrete Forms." 2005. http://www.forms.org/

Incropera, Frank and DeWitt, David. *Introduction to Heat Transfer 4th ed.* Wiley and Sons, 1996.

Inflation Data. "Annual Inflation Rate Chart." 2006. http://inflationdata.com/inflation/Inflation_Rate/AnnualInflation.asp

Jeoun, Jimmy J. "Using Value Focused Thinking to evaluate the practicality of ground source heat pumps at military installations." MS thesis, AFIT/GEM/ENS/05M-01. School of Systems and Engineering Management, Air Force Institute of Technology (AU), Wright-Patterson AFB OH, March 2005.

Keeney, Ralph L. and Raiffa, Howard. *Decisions with Multiple Objectives: Preferences and Value Tradeoffs.* Cambridge University Press, NY. 1993.

Keeney, Ralph L. *Value-Focused Thinking: A Path to Creative Decision making*. Cambridge MA" Harvard University Press, 1992.

Kirkwood, Craig W. *Strategic Decision Making: Multiobjective Decision Analysis with Spreadsheets.* Duxbury Press, Belmont, CA, 1997.

Lawrence Berkley National Laboratory (LBNL). "Cool Roofs." 2000. http://eetd.lbl.gov/HeatIsland/CoolRoofs/

Leon, O.G. "Value-Focused Thinking versus Alternative-Focused Thinking: Effects on Generation of Objectives." Organizational behavior and human decision processes. Vol 80, Issue 3. 1999.

Mills, A.F. *Heat Transfer 2nd ed*. Prentice Hall, 1999.

Northeast Regional Climate Center. "Comparative Climatic Data For the United States." 2006. http://www.nrcc.cornell.edu/ccd.html

Parker, Danny S. et. al. "Measured Cooling Energy Savings From Reflective Roofing Systems In Florida: Field And Laboratory Research Results." Florida Solar Energy Center (FSEC), FSEC-PF-293-95, 1995

Reward Walls. "Reward Walls Participate in ICF Blast Demonstration." www.rewardwalls.com/newsletter_summer2003.pdf. 2003.

Santee Cooper. "Mercury Rising? Cool Roofs Help Beat the Heat." 2006. http://www.santeecooper.com/yourbusiness/Commercial_Saver/Final%20PDFs/MercuryRising_CoolRoofsHelpBeattheHeat.pdf.

Schanding, Gregory T. "A Value Focused Thinking Model for the Development and Selection of Electrical Energy Source Alternatives at Military Installations." MS thesis, AFIT/GEM/ENS/04M-02. School of Systems and Engineering

Management, Air Force Institute of Technology (AU), Wright-Patterson AFB OH, March 2004.

Schmidli, Robert J. "CLIMATE OF PHOENIX, ARIZONA: An Abridged On-Line Version of NOAA Technical Memorandum NWS WR-177." Arizona State University, 1996.

Shoviak, Mark J. "Decision Analysis Methodology to Evaluate Integrated Solid Waste Management Alternatives for a Remote Alaskan Air Station." MS thesis, AFIT/GEE/ENV/01M-20. School of Systems and Engineering Management, Air Force Institute of Technology (AU), Wright-Patterson AFB OH, March 2001.

SIP Association. "Structural Insulating Panels." 2005. http://www.sips.org/

Spradlin, Tom. "The Lexicon of Decision Making." 2005. http://faculty.fuqua.duke.edu/daweb/lexicon.htm

Staats, Raymond W. Class notes, OPER 643, Advanced Decision Analysis: Multiple Objective Decision Analysis. School of Engineering and Management, Air Force Institute of Technology, Wright-Patterson AFB OH, Spring Quarter 2005.

Turner, Wayne and Elder, Keith. *Energy Management Handbook*. The Fairmont Press, 2001.

Trumbore, Brian. "The Arab Oil Embargo of 1974-74." 2002. http://www.buyandhold.com/bh/en/education/history/2002/arab.html

United Facilities Code. *Design: Energy Conservation.* UFC 3-400-01. 5 Jul 2002. http://www.hnd.usace.army.mil/techinfo/ufc/081602_UFC3-400-01.pdf

University of Wisconsin-Milwaukee. "Great Lakes WATER Institute Green Roof Project." 2006. http://www.uwm.edu/Dept/GLWI/ecoli/Greenroof/roofinstall.html

Velazquez, Linda S. "Organic Greenroof Architecture: Sustainable Design for the New Millennium." *Environmental Quality Management.* Summer 2005.

Western Regional Climate Center. "Denver, Colorado. Normals, Means, and Extremes." 2006. http://www.wrcc.dri.edu/cgi-bin/clilcd.pl?co23062.

Wikipedia. "1973 Oil Crisis." 2005. http://en,wikipedia.org/wiki/1973_energy_crisis

VITA

Captain David M. Pratt graduated from Adrian High School in 1995 in Adrian, Michigan. He then attended the University of Michigan in Ann Arbor, and graduated in 2001 with a Bachelor of Science degree in Engineering with a focus on Mechanical Engineering. Captain Pratt was commissioned through the Air Force Reserve Officer Training Corps Detachment 390 at the University of Michigan-Ann Arbor.

Captain Pratt's first assignment after commissioning was with the 78th Civil Engineer Squadron at Robins AFB, Georgia in May 2001. There he served as a mechanical engineer in the Maintenance Engineering Flight, as well as the Readiness Flight Commander. He deployed in support of Operations SOUTHERN WATCH, IRAQI FREEDOM and ENDURING FREEDOM in March 2003 to Doha International Air Base, Qatar (known as "Camp Snoopy") and served as Chief of Engineering and Operations with the 64th Expeditionary Civil Engineering Squadron. In August 2004, Captain Pratt entered the Graduate School of Engineering and Management, Air Force Institute of Technology, Wright Patterson AFB, Ohio. Upon graduation Captain Pratt will be assigned as Commander, Environmental Flight, 65th Civil Engineering Squadron, Lajes AB, Azores, Portugal.

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Graduate School of Engineering and Management (AFIT/EN)
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WPAFB OH 45433-7765

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HQ AFCESA/CESM
Attn: Mr. Tim K. Adams
139 Barnes Drive Suite 1
Tyndall AFB FL 32403-5319 DSN: 523-6168

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14. ABSTRACT

The Department of Defense (DoD) has hundreds of thousands of facilities in its inventory, which consume billions of BTUSs of energy per year. Much of that energy is used to heat and cool the facility, and a great deal of this energy is lost through the building envelope. While new military construction works towards energy efficiency, the majority of DoD facilities were built over forty years ago with little regard to energy efficiency, and it is these facilities that have the greatest potential for energy efficient building envelope retrofits. There are hundreds of various new building envelope technologies available to retrofit an existing building envelope, including window, roof, and wall technologies. This research investigated fifteen different building envelope technologies and found that many of them are feasible alternatives for DoD facilities. Value Focused Thinking (VFT) was the methodology used to objectively compare these new technologies and capture what Air Force decision makers value in regards to retrofitting older facilities with these new building envelope technologies. Data from three different Air Force bases and values from three different Air Force Civil Engineer Operations Flight Chiefs were used to evaluate these fifteen technologies, and the results show that the energy efficient window technologies have the highest potential for energy savings at each location. However, the research also shows that each of these technologies is a viable option and should always be considered when retrofitting an existing facility.

15. SUBJECT TERMS
Energy Efficient, Building Envelope, Retrofit, Facilities, Value Focused Thinking

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					Ellen C. England, Lt Col, USAF (ENV)
REPORT	ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(Include area code)*
U	U	U	UU	125	(937) 257-3636, ext 4711; e-mail: Ellen.England@afit.edu