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Enhancing the Thermal Performance of Temporary Fabric Shelters for the Advanced Energy Efficient Shelter System

Justin E. Eshleman

ENHANCING THE THERMAL PERFORMANCE OF TEMPORARY FABRIC SHELTERS FOR THE ADVANCED ENERGY EFFICIENT SHELTER SYSTEM

THESIS

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Abstract

The purpose of this research was to aid the Air Force Civil Engineer Center with the development, testing, and analysis of Advanced Energy Efficient Shelter Systems—ultimately leading to the procurement of next-generation shelter systems. Specifically, this research focused on the thermal performance of radiant barrier technology integrated into different types and configurations of fabric materials used for the fly, skin, and liner of temporary fabric shelter. The absence of testing standards specific to the thermal performance of temporary fabric shelters required testing procedures and thermal performance metrics to be analyzed and established. Then, a design of experiments was conducted using a modified hot box apparatus and small-scale test jigs resulting in over 57,350,000 data points capturing exterior climatic conditions and resulting temperatures of the materials and interior space. Comparisons of means and correlations were used to identify the optimal number of layers, number of radiant barriers, and placement and direction of radiant barriers. As a result, hot box air conditioning runtimes were reduced up to 54.6% compared to standard single-layer systems while test jig interior temperatures decreased as much as 14.8°F. Finally, multiple regression modeling of thermal performance confirmed the best two- and three-layer fabric systems.

Dedication

Thank you to my wife and baby girl, the loves of my life, for supporting me through this adventure.

Acknowledgments

I would like to thank my committee, especially Dr. Coutu and Dr. Lake for the guidance and mentorship throughout my time at the Air Force Institute of Technology. Thank you Mr. Fisher, Dr. Moheisen, and the rest of the team at the Air Force Civil Engineer Center (AFCEC) for the wealth of information on temporary fabric structures. Also, thank you Mr. Lehman for involving me in the fabrication of the next-generation shelters. Finally, I would like to thank Lt Blach for the MATLAB coding and Professor Turner and Dr. Laurvick for the edits and suggestions.

Justin E. Eshleman

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I. Introduction

The price of fuel is high, but the cost is much greater. This cost is most apparent in locations at the end of long supply chains, like a remote forward-operating base in the Middle East. In fiscal year 2007, convoys transported 504 million barrels of fuel in support of military operations in Afghanistan and Iraq. This required approximately 6,000 fuel convoys resulting in 170 casualties [1-2]. According to a 2009 Army Environmental Policy Institute's technical report, fuel supply convoys averaged one casualty per 38.5 convoys in Iraq and one casualty per 23.8 fuel convoys in Afghanistan [2]. The further the fuel must be transported, the higher the risk and the higher the cost. Reducing fuel consumption in the deployed environment also increases tactical abilities. At the tactical level, "reducing dependence on large liquid fuel supply lines enhances the ability to disperse, maneuver and operate over long distances and conduct operations in remote locations" [3].

The largest single energy consumer for base operating support in austere locations is the electrical load for cooling shelters [4]. Thermally inefficient shelters create massive cooling loads. By increasing the thermal efficiency of shelters, less energy will be required to cool the shelters, thus requiring less fuel, fewer convoys, and less risk to the mission. Increasing the thermal performance of temporary fabric shelters will directly impact the demand for fuel in the deployed environment and improve operational security.

1.1 Background

According to the Department of Defense's (DoD) 2014 Operational Energy Annual Report, the DOD "consumed an estimated $14 billion of operational energy, with more than 54 percent of that purchased outside of the United States" [3]. In an effort to minimize this vulnerability, the DOD issued Directive 4180.01 outlining policy to "enhance military capability, improve energy security, and mitigate costs in its use and management of energy" [5]. This policy aimed to improve equipment and installation performance, at both enduring and non-enduring locations, while expanding energy supplies and sources to include alternative energies. Furthermore, Directive 4180.01 called for the development and acquisition of technologies to meet DOD energy needs and manage risk.

Operational energy consists of "energy required for training, moving, and sustaining military forces and weapons platforms for military operations. The term includes energy used by tactical power systems and generators and weapons platforms" [3]. This research focuses on the energy required to operate contingency bases in austere locations. An estimated 59-67% of the overall base operating support electrical load is for heating, ventilation, and air conditioning (HVAC) [6-8]. Compared to permanent structures, the soft walls of temporary fabric tents are inherently thermally inefficient. For this reason, the Air Force and Army collaborated on a group project to develop and demonstrate deployable Advanced Energy Efficient Shelter Systems that are 50% more energy efficient than current shelters. To achieve this goal, the development of solar flies, insulated tent liners, more efficient Environmental Control Units (ECUs), vestibules, and energy efficient lighting is currently being tested and evaluated in field conditions. These advancements have the potential to reduce point-of-use energy consumption and reduce the amount of fuel required to operate a contingency base.

Murley [9] developed a method to capture the fully-burdened cost savings of implementing energy efficient systems across the entire supply system. This method considered the efficiencies gained from the use of solar flies in different climates. His research incorporated geographic information system (GIS) climate and transportation data to analyze the cost implications of point-of-use energy consumption (energy used by the ECU) savings in order to provide decisions makers with a tool for implementing energy efficient systems [9].

While Murley's research focused on high level decision making, this research will identify and improve the material properties and performance of shelters. Very few publications on the thermal properties of temporary fabric structures exist, besides studies performed by the DoD. Even fewer studies exist on the use of radiant barrier technology in temporary fabric structures. This required the literature review to examine other related fields, mainly the traditional construction industry and textile industry. Research on radiant barriers in residential attics has proven the effectiveness of this technology in traditional home construction [10]. Then, case studies of existing fabric roof structures and their thermal performance provide insight to the optical properties relevant to heat transfer through fabric layers, laying the foundation for testing and measuring the thermal performance of temporary fabric structures [11-13].

However, there is no standard metric used to measure the thermal performance of radiant barrier technology in temporary fabric shelters. Currently, the Air Force measures the efficiency of the shelter by the amount of power required to cool the interior space; the Army attempts to assign an equivalent R-value. Similar research on the use of radiant barriers in attics measure heat flux [10, 14]. A standardized metric must be determined to fully capture the thermal properties of the materials and overall performance of the structure as a system. Then, the thermal performance of potential next-generation shelters can be evaluated.

1.2 Purpose

Current skin and liner temporary fabric structures are not efficient barriers for preventing heat transfer. The thin, uninsulated floors, walls, and ceiling allow heat to penetrate easily into the conditioned space causing an enormous cooling load. This load is exacerbated by the extreme heat experienced in the Middle Eastern climate. To maintain a comfortable temperature within the structure, large five-ton ECUs are required for every small shelter. Thermally inefficient shelters paired with large ECUs create a high fuel demand.

The purpose of this research is to aid the Air Force Civil Engineer Center (AFCEC) with the development, testing, and analysis of Advanced Energy Efficient Shelter Systems—ultimately leading to the procurement of the next-generation shelter systems. Specifically, this research will help develop an accurate evaluation method for the thermal performance of fabrics used in the shelters, enhance the thermal properties of shelter materials through the use of solar reflective coatings, and determine how to scale the technological advances of small shelters to medium and large shelters.

This research will focus on small, medium, and large shelters in hot, dry climates and will accomplish the following:

1. Determine how to measure thermal performance of fabric structure materials.
2. Determine the most thermally efficient material composition of fly, skin, and liner.
3. Determine the most thermally efficient configuration of fly, skin, and liner.
4. Determine if the same technology can be applied to medium and large shelters.

1.3 Methodology

AFCEC provided data gathered from the development and testing of Advanced Energy Efficient Shelter Systems for analysis along with experimental data collected in coordination with shelter manufacturers. Statistical analysis of data obtained from the manufacturer's hot box test and AFCEC's small-scale test jigs allowed the researcher to determine the key variables correlating climatic conditions and materials used with overall shelter performance. Then, using these variables, the materials and configurations were optimized through a Design of Experiments (DOE) incorporating a modified hot box method along with field tests in cooperation with AFCEC.

1.4 Assumption and Limitations

This research attempts to address a specific, real-world problem affecting military operations in its current environment. The goal is to reduce the heat load on the temporary fabric structures to optimize performance in hot, dry climates. The optimal solution for hot, dry climates may not be effective for temperate or cold climates. Further research is necessary to optimize the performance for other climates.

Next, the researcher assumes that it is not practical to have an outer fly layer for the medium and large shelters. Outer flies are currently installed on small shelters by throwing ropes over the structure and four Airmen pulling the fly over top. This method is not practical for medium and large shelters as the fly would be too heavy to pull. Due to this limitation, the medium and large shelters will be optimized only using two layers.

1.5 Implications

The DoD aims to procure more energy efficient temporary fabric structures to reduce the amount of operational energy used in the contingency environment. In order to develop a contract for the next-generation shelters, AFCEC must set a realistic benchmark for shelter performance and identify a standard procedure to evaluated competing shelters. This research will aid AFCEC with the development, testing, and analysis of shelter materials and identify the optimum configuration of the fly, skin, and liner system. Additionally, this research will set a standard measurement process for the thermal efficiency of temporary fabric structures. The energy saved by these new structures will reduce the point-of-use fuel consumption down range, minimizing the amount of fuel convoys, and reducing risk to mission.

1.6 Preview

The next four chapters will contain further detail of the problem statement, methodology, and results. A review of past research of temporary fabric structures, radiant barriers, and the procedures for measuring thermal performance of structures is provided in Chapter II. A further defined research scope and explanation of the methodology used to collect and analyze thermal performance of materials is presented in Chapter III. Chapter IV provides a discussion of the data collected and analysis of fabric structure material performance. Finally, Chapter V contains research conclusions, limitations, and offers recommendations for future research.

II. Literature Review

This chapter provides evidence and justifies the need for thermally efficient temporary fabric structures for military use. The current skin and liner systems are not efficient in the hot, dry climate of the Middle East. The Department of Defense (DoD) needs to establish a benchmark as to the possible performance capabilities of temporary fabric shelters to create realistic contract specifications for future shelter acquisition. Material properties, material configurations, and environmental variables affecting thermal performance must be identified and defined. Then, a testing procedure and standards must be developed to compare different shelter systems.

First, the need for climatically-controlled environments is established. Then, an investigation into the evolution of fabric shelters demonstrates the technological advancements in the material properties of fabrics. The concept of multiple-layered shelter systems with radiant barriers is explained along with the difficulties of accurately capturing the efficiencies of these systems. To determine the most appropriate and useful measurement of heat transfer, other industries and their standards are considered. Identifying and filling the knowledge gap in measuring thermal performance of temporary fabric structure systems allows the optimization of material composition and configuration of fly, skin, and liner.

By optimizing the fabric shelter system, massive point-of-use power saving may be achieved in the deployed environment. The amount of fuel and Environmental Control Units (ECUs) can be reduced. This will equate not only to cost savings in fuel but mitigation in risk and use of manpower required to deliver the fuel to austere locations. Furthermore, the decreased dependency on fuel allows for increased range and force maneuverability.

2.1 Thermal Comfort

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) is a world leader in the development of standards and research for the environmental control of the indoor environment [15]. According to ASHRAE, the thermal conditions of the environment affect people physically, physiologically, and psychologically. The human body self-regulates temperature through physiological processes to prevent overheating (hyperthermia) and overcooling (hypothermia) referred to as "human thermoregulation" [15]. If the environment is too hot or cold, the human body will suffer both physically and psychologically, leading to discomfort, decrease in performance, and other adverse effects such as heat stroke. For these reasons, it is important to control the internal work and home environments in which the external environment does not provide adequate thermal comfort.

Nine main variables are used to characterize the thermal environment: air temperature, wet-bulb temperature, dew-point temperature, water vapor pressure, total atmospheric pressure, relative humidity, humidity ratio, air velocity, and mean radiant temperature [15]. In the indoor environment, the building envelope and HVAC are used to control these variables by controlling the temperature, humidity, and pressure. These variables can be adjusted to achieve an optimum thermal comfort for the occupants or building use. Military operations require environmental control for equipment such as computers, servers, and aircraft in addition to comfort cooling. The target comfort range is established, and HVAC systems are designed based on the external environment and interior requirements. The hot, dry climate of the Middle East requires the use of ECUs to cool the temporary fabric shelters to a point where they are comfortable for sleeping, working, and any other activities that are supported by the structures. ECUs are the current method used to control the indoor environment, but the challenge of creating a comfortable environment is not a new problem.

2.2 History of Temporary Fabric Structures

Temporary fabric structures are of particular interest to the DoD, but tent-like structures have been around since the beginning of civilization. According to Genesis 18:1, "The LORD appeared to Abraham near the great trees of Mamre while he was sitting at the entrance to his tent in the heat of the day." Abraham used his tent to shield himself from the sun's radiation to keep himself cool. Temporary fabric shelters like this provide protection from the exterior environment and an ability to regulate the interior environment. Shelters were made of locally-sourced materials and customized to the environment in which they performed.

The Native American tribes used a variety of different shelter types, many of which are the same pole frame with protective skin used today. Tepees were used by Plains tribes and built of wood poles and buffalo hides that could be transported with them as they migrated. Ventilation flaps were designed into the structure to allow for a fire within the tent. Some tepees were outfitted with an inner liner that provided an insulating air gap in the summer and could be filled with grass for extra insulation in the winter [16]. Similarly, in Central Asia, traditional yurts were used by nomads. These structures were slightly more sophisticated with walls and a roof frame built of wood, covered by a tensioned felt made from sheep's wool, which is a natural insulating material [17]. As civilization progressed, the need to migrate with food sources declined and led to more permanent structures. However, the need for temporary fabric shelter continues to exist.

2.3 Current Uses of Fabric Structures

Today, many examples of both temporary and permanent fabric structures exist throughout the world. Fabric shelters are popular because they can be erected more quickly and cheaply than traditional building methods. Fabric structures are categorized as either "tensile fabric structures" or "pneumatic structures." Tensile fabric structures consist of "a membrane supported by masts or other rigid structural elements such as frames or arches," while pneumatic structures "depend on air pressure for their stability" and loadbearing capacity [18]. The continually advancing textile and materials industry engineers materials that are stronger, longer lasting, waterproof, and flame resistant. These engineered properties allow for a wide range of uses.

Tensile fabric structures are widely available for recreational purposes such as camping. These tents provide shade from the sun and can be vented on the sides but are generally passive systems and are not engineered for thermal performance in hot weather. Similarly, event tents for large gatherings provide shade and ventilation but are not engineered for thermal performance. These very basic temporary fabric structures provide passive relief from the direct sun but do not actively control the interior environment.

More sophisticated examples of permanent fabric structures include roofs of large buildings like airports, convention centers, and sporting arenas. Fabric structures are used in these cases due to their light-weight properties along with their relative ease of construction. A 210-foot by 900-foot section of the Denver International Airport is covered by a white, double-layered polytetrafluoroethylene fabric (Teflon®-coated woven fiberglass membrane). A case study by Barden [12] confirmed the energy efficiency of the roof membrane, reflecting 76% of all incident solar radiation, while absorbing only 15% as heat due to its low thermal mass. The remaining 9% is transmitted through the fabric as light—decreasing the need for artificial lighting [12]. Similar technology is used in hot climates as well. The King Abdulaziz International Airport (KAIA) in the Kingdom of Saudi Arabia is constructing the largest fabric structure of its kind at five million square feet. The tent-like structure adds versatility, as it can be folded up when not in use for the annual mass pilgrimage to Mecca [13]. The concept of radiant barriers allows for enhanced thermal properties without the extra weight and bulk of insulation. The increased use and research into fabric materials in industry will be used to enhance the military temporary structures.

2.4 Current Military Shelters

The military requires a higher performance level from temporary fabric structures compared to the average consumer. More demanding specifications for the constructability, durability, livability, and special functions for military use are necessary for operations in the deployed environment. Earlier versions of the shelters placed higher importance on other factors at the expense of thermal performance, which could be made up by the ECU. Realization of the true cost of fuel and advancements in technology has required thermal performance to be integrated into the design without major degradation to other factors—mainly size and weight.

Specifications for the constructability and resilience of the fabric structures must include speed and ease of construction, high tear strength, puncture resistance, reparability, flexibility, light weight, as well as long life span both in-use and in-storage. The shelters must be safe and livable, meaning waterproof, flame resistant, non-toxic, low odor, and mildew resistant. Finally, the shelter fabric must address operational concerns including color, opacity, resistance to oils, chemicals and biologics, and have infrared reflectance and blackout properties. The aforementioned properties must now include a measure of thermal efficiency.

The United States Air Force (USAF) currently uses the Basic Expeditionary Airfield Resources (BEAR) mobile assets for bare base deployments to “rapidly open an airfield, generate a specified sortie level, establish operational capabilities and conduct air operations” [19]. The BEAR system consists of water purification and distribution equipment, power generation, fuel storage, troop billeting, field services, and everything else needed to open and operate a base. This research will focus on the shelters and ECUs. The USAF mainly utilizes four different shelter systems: the Small Shelter System (SSS), the Medium Shelter System (MSS), the Dome Shelter, and the Large Area Maintenance Shelter (LAMS), pictured in Figures 2-5. The use, size, and set-up time for each system is listed in Table 1. The Tent, Extendable Modular Personnel (TEMPER) is mainly used by the United States Army but will also be considered in this research.

All shelters are soft-walled, frame-supported tensile fabric structures. The shelters only require the “skin” layer over the frame, but additional liners and outer flies can be added to enhance the thermal performance of the shelter. The TEMPER, in Figure 1, is fitted with an outer fly with an air gap above the skin. This effectively shades the skin and allows ventilation—cooling the roof and enhancing the thermal performance of the shelter. The SSS in Figure 2 can be outfitted with an interior liner, which is white on the interior side and reflective on the exterior side and provides some thermal benefits. The size and current design of the medium and large shelters make it prohibitive to add additional fabric layers, as there is no way to install them without specialized equipment.

Table 1: Air Force shelter specifications

Classification	Name	Purpose	Dimensions (feet, LxWxH)	Area (sq ft)	Set-up time (man-hours)
Small	Small Shelter System (SSS) – Figure 2	General purpose: billeting, offices, field services, showers, storage	32.5 x 20 x 10	650	9
	Tent, Extendable Modular Personnel (TEMPER) – Figure 1	General purpose: billeting, offices, field services, showers, storage	32 x 20 x 11	640	9
Medium	Medium Shelter System (MSS) – Figure 3	Maintenance operations, warehouse, kitchen	52 x 29.5 x 15	1,534	24
Large	Dome Shelter – Figure 4	Aircraft hangar, maintenance facilities, warehouses, mess halls, and billeting	70 x 116 x 25	8,120	256
	Large Area Maintenance Shelter (LAMS) – Figure 5	Aircraft hangar, vehicle maintenance	129 x 75 x 31	9,675	300

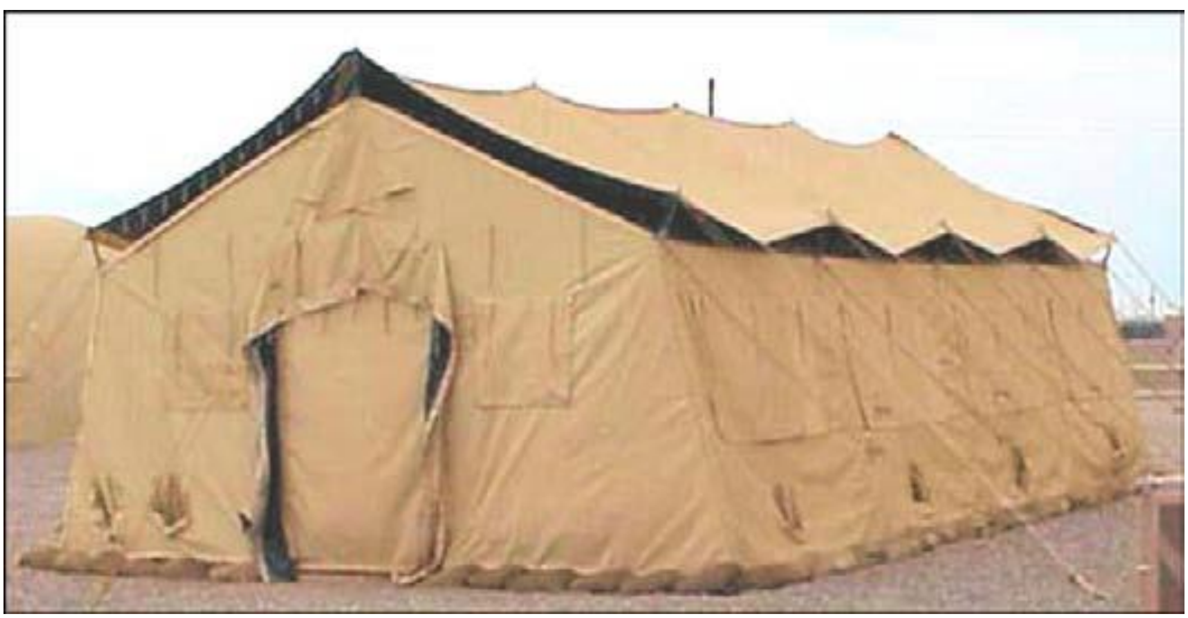

Figure 1: TEMPER, small shelter typically used by the Army [19]

Figure 2: SSS, small shelter typically used by the Air Force [19]

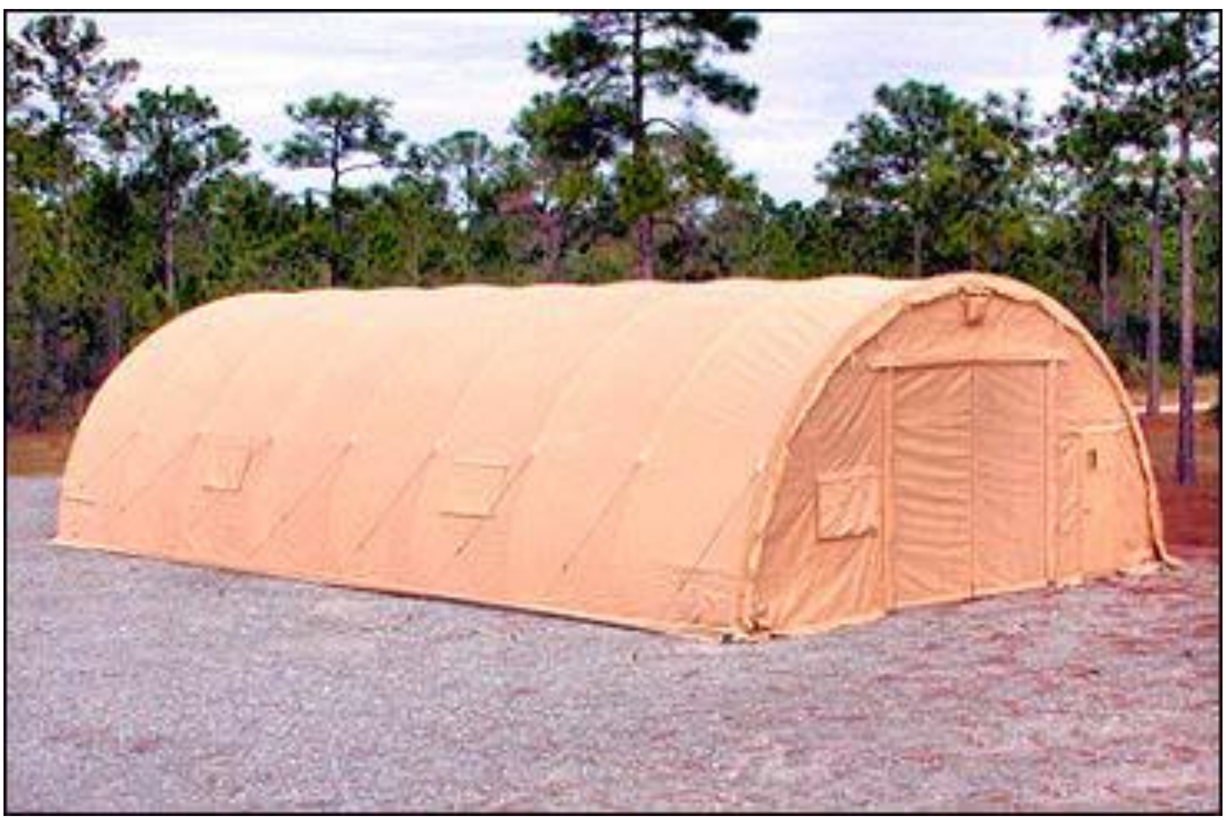

Figure 3: MSS, medium shelter typically used by the Air Force [19]

Figure 4: Dome Shelter, large shelter used to house aircrafts [19]

Figure 5: LAMS, large shelter used to house aircrafts [19]

2.5 Efficiency of the Environmental Control Unit

The Environmental Control Unit (ECU) is an air conditioning and heating unit specifically designed for use in deployed locations. The approximately 750-pound unit produces up to 67,000 BTUH for cooling and 84,000 BTUH for heating with an air flow of 2200 cubic feet per minute. A small shelter will have one ECU while larger shelters may have multiple ECUs [20]. The efficiencies of current and future ECUs are beyond the scope of this research; however, these factors play an important role in the overall performance of the system as they are the point-of-use for energy consumption. The thermal performance of the materials and configurations of the shelter fabrics can be optimized without the use of the ECU.

2.6 Applying Traditional Construction Techniques to Fabric Shelters

Fabric shelters are inherently less protective than traditional construction. The entire envelope is soft, thin, and lightweight compared to traditional stick frame or masonry construction. In traditional buildings, the building envelope is defined as "the parts of the building, principally the walls, roofs, and fenestration, that separate the interior of the building from the exterior, and that must effectively control the flow of heat, air, and moisture" [8]. In short, a building envelope provides protection from the elements. Part of the protection provided includes thermal protection. This protection is achieved in part by passive systems that control air leakage and heat transfer. Combinations of materials are used to seal and insulate buildings from the elements including roof systems, siding, house wrap, sheathing, and insulation. In fabric structures, the building envelope is a single piece of fabric or system of multiple fabrics.

Traditional building systems encounter each of the three forms of heat transfer, but systems generally only account for conduction and convection through the use of insulation and ventilation. The source of the problem, radiation, is "largely ignored" [21]. When radiation in the form of electromagnetic waves from the sun hits a roof, it can be reflected, transmitted, or absorbed. The amount of each depends on the wavelength of the radiation and the properties of the roofing material [3]. Figure 6 illustrates this concept on a typical, asphalt-shingled, residential pitched-roof surface. The heat absorbed by the shingles transfers to the cooler sheathing through conduction [10]. When the sheathing becomes hot, it radiates heat through the attic air to the cooler insulation and ceiling structure. The insulation acts as a buffer to slow the transfer of heat to the conditioned space but will ultimately radiate heat and warm the conditioned space. Attic vents are used to help cool the attic space through convection, but this alone is not enough as attic spaces can become warmer than the outside temperature during summer.

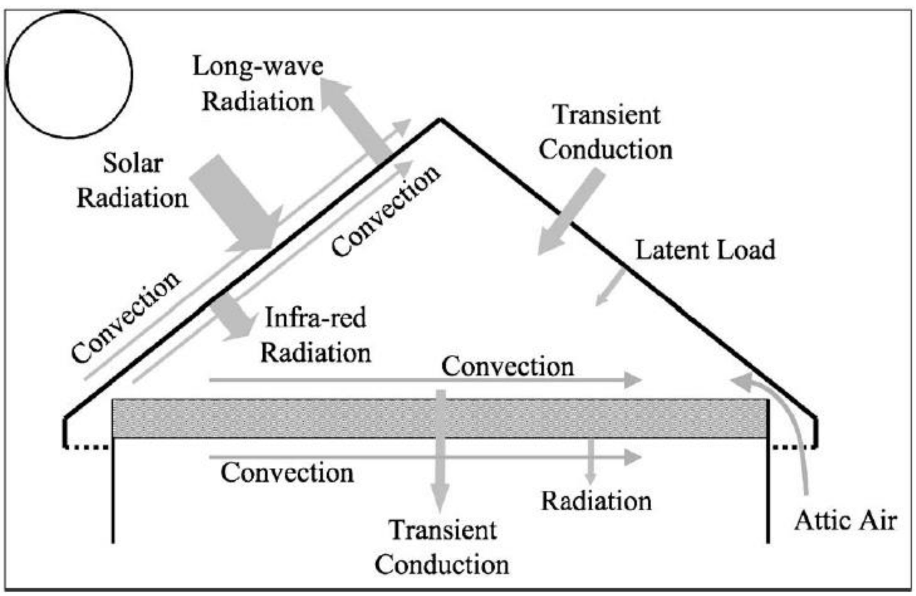

Figure 6: "Attic geometry and thermal and mass exchanges" [10]

Recent research suggests that stopping the radiation at the surface of the roof will produce large gains in warm climates, enhancing thermal efficiency [8, 10, 22]. Materials called radiant barriers can be incorporated into buildings to counteract heat transfer due to radiation of the roof and attic space. Similar technology exists in windows with low-emissivity glass which are analogous in principle to a cool roof. In typical home construction, a radiant barrier is a foil layer, similar to a space blanket, connected directly to the rafters or laid over the insulation. While a shiny, reflective surface is not conducive to concealment in the deployed environment, the concept of radiant barriers should be applied to temporary fabric shelters, as they are thin and light weight.

2.7 Radiant Barriers

Radiant barriers are a type of reflective insulation. This research will use the American Society for Testing and Materials (ASTM) International definition for reflective insulation, stated as an insulation that reduces "radiant heat transfer across air spaces by use of one or more surfaces of high reflectance and low emittance [0.1 or less]" [23]. The two properties qualifying a material as a radiant barrier are high reflectance and low emittance. High solar reflectance equates to low heat absorption, whereas low thermal emittance equates to low radiation of stored heat [8]. However, these material properties alone do not capture the performance of a radiant barrier system, which is the combination of an open air space with radiant barriers [24]. Instead, an "equivalent thermal resistance of the air chamber" is required; however, there is no standard for measuring the performance of radiant barrier systems resulting in inconsistent testing and measuring conditions [25]. Even less is known about modeling radiant barriers in fabric structures [9].

2.8 Heat Transfer through Fabric Shelter Systems

The building envelope of temporary fabric structures contains up to three different layers, the outer fly, the skin, and the inner liner, plus the air spaces in between the layers. Each layer may be a different material with different thermal properties. To analyze the shelter as a complete system, all three components of heat transfer (radiation, convection, and conduction) must be considered.

2.9 Heat Transfer through Fabric Layers

The fabric layers have to fulfill a variety of purposes other than just insulation. Shelters must also be waterproof, high strength, tear and puncture resistant, compact, lightweight, and easily transported. These requirements rule out foam or fiberglass insulation used in traditional construction. However, fabrics can mitigate all three methods of heat transfer: conduction, convection, and radiation. The thermal properties of fabrics are dependent on many factors. The material type, thickness, density, and orientation of fibers all contribute to the conductive resistance of the material [26]. The processing and finishing of the raw materials used also effects the thermal properties; increasing the air permeability of the fabric promotes convective cooling as air passes through the material [27]. For radiation, the optical properties of the material will affect how much light is absorbed, reflected, or transmitted through the fabric. The materials used in modern fabric shelters are blends including vinyl coated polyesters and polytetrafluoroethylene coated fiberglass [12]. These materials are thin and ineffective in terms of conductive heat transfer with R-values around 0.02 [28]. Therefore, technologies targeting heat transfer due to radiation are considered.

The thermal properties of the fabric materials are enhanced when a radiant barrier is incorporated into the fabric. In general, insulation placed "closest to the point of entry of heat flow" results in the best thermal performance [29]. Conversely, Riemer [28] reasons that it is equally efficient to place radiant barriers on the outside surface of the liner, under the skin layer. However, Riemer [28] used a reflective aluminum laminated fabric, which drove his decision to place the layer inside where it would not interfere with the camouflage properties of the shelter.

Current technology now allows radiant barriers to be incorporated into the fabric while maintaining a camouflaged appearance. The optimum radiant barrier placement within the system will be explored further in this research.

2.10 Heat Transfer in the Air Spaces

Multiple air spaces exist in the shelter system including the ambient air space, the internal conditioned air space, and the air gaps between the fly and skin layer, and the skin and liner layer. The interior air space will be controlled by the ECU while the ambient temperature will be dependent on the environment. For this research, the internal temperature was set using ASHRAE's recommendations and the external temperatures was set according to the characterization of the Middle East. The temperatures of the air spaces between the layers are of interest.

The outer fly of the tent is approximately two inches from the tent skin. This air gap not enclosed, allowing air to flow through the space depending on wind speed and direction, see Figure 7. According to Reimer [28], this results in either a positive or negative effect on the thermal performance, depending on the conditions. A ventilated space is advantageous as it allows for convection cooling on either side of the fly layer and outside of the skin layer. However, the air space is only effective as insulation if the air is still [28]. The tradeoff in thermal efficiencies of ventilated air space versus dead air space between the fly and skin layers will require further investigation and experimentation.

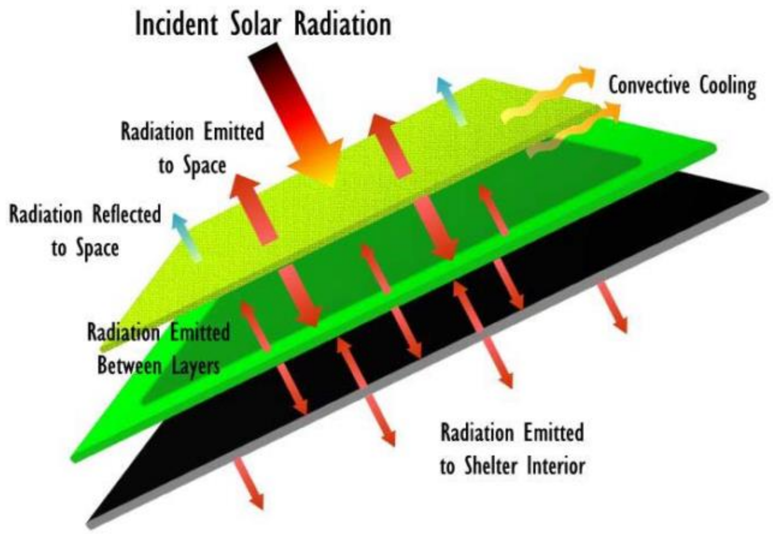

Figure 7: Heat transfer through fabric layers [28]

The space between the skin layer and liner is designed to be a dead air space and airtight to maximize the insulation value. In this idealized situation, heat flow across the air spaces will be "affected by the nature of the boundary surfaces, orientation of the air space, distance between boundary surfaces, and direction of heat flow" [15]. The radiation component depends on the material properties of the fabric layers, namely the reflectivity, emissivity, and absorptivity. The hotter material will radiate heat through the air space to the cooler material until equilibrium is reached. The two surfaces will interact and produce an effective emittance [15].

However, Riemer [28] observed convection currents present in the dead air space, as the hotter air rises and cooler air falls. He argues the convective currents are the "largest area of heat transfer that has not been addressed" by shelter manufacturers [28]. Baffles may be added to the air space to prevent these currents, but is not part of this research. Additionally, there is likely an optimal gap distance between the layers. Optimizing the air gap is not a part of this study.

2.11 Other Heat Transfer

Due to shelter design and construction, conduction will occur through thermal bridging of the outer fly layer to the structural members of the shelter frame, then from the shelter frame to the middle skin layer. The amount of heat flow will depend on the amount of contact area between the structural members and the fabric layers, and the material properties of the structural members. Because the structural members of next-generation structures are unknown, this research focuses on the interaction of the fabric layers and the air spaces between them, neglecting the conduction component caused by thermal bridging.

Infiltration and exfiltration of air is another concern for the shelter thermal efficiency. The unintentional flow of air in or out of the structure can occur through fenestrations, holes, or faulty seams. In general, the temporary fabric structures do not have many openings and are designed to be air tight. One obvious source of air leakage is through the door when opened. Air Force Civil Engineer Center (AFCEC) added a vestibule with an additional door to address this problem. With only one door open at a time, the amount of air exchanged is greatly reduced.

2.12 Summary

Very few publications on the thermal properties of temporary fabric structures exists, besides studies performed by the DoD. Even fewer studies exist on the use of radiant barriers in temporary fabric structures. This required the literature review to examine other related fields, mainly the traditional home construction industry and textile industry. Test and evaluation standards related to these industries will be adapted to access the thermal performance of fabric structures.

III. Methodology

A standardized process for measuring the thermal performance of temporary structures with radiant barriers for military use does not exist. Because there is no standard, different entities involved in the development of temporary structures are using different methods, different variables, and quantifying thermal performance differently. Since the military is currently driving the demand for these structures, they must set the standard and test methods for which competing bids for next-generation shelters will be evaluated. However, there are differences among the branches of the Department of Defense (DoD) as to how to measure the thermal performance.

The Air Force measures power required to run the air conditioner (A/C), while the Army uses an R-value. The problem with using an R-value is that it does not directly capture the performance of the radiant barrier. Therefore, an equivalent R-value is assigned. The Air Force measures the thermal performance of full-scale tests by the amount of power drawn from the Environmental Control Units (ECUs) to keep a structure cool. This method is advantageous, as it directly measures the value the military is ultimately interested in and evaluates the structure as a whole. However, the Air Force's method can introduce error, as the actual efficiency of the ECUs might vary—skewing the data.

Currently, the Air Force has three main data sources. The first set of data comes from a tent manufacturers that uses a modified hot box apparatus method to evaluate the thermal properties of the fabric materials individually and as systems of liner, skin, and fly. The second source of data is from Air Force Civil Engineer Center (AFCEC), in which they set up small-scale test jigs at Tyndall Air Force Base. These test jigs are outside and exposed to the "real world" environment. Finally, the third set of data from AFCEC includes full-scale tests on shelters with different liner, skin, and fly configurations located in Ali Al Salem Air Base, Kuwait; Tyndall Air Force Base (AFB), Florida; Holloman AFB, New Mexico; and Anderson AFB, Guam. For the full-scale test, a combination of weather data, interior environmental conditions, and ECU power usage was recorded.

There are hundreds of different products on the market that could be used to construct temporary fabric structures with millions of different combinations of liners, skins, and flies with varying air gaps; this research used products from three different textile producers for military application. Each of these technologies can meet the current specifications for military fabrics and adhere to the Berry Amendment, which restricts the use of "fabrics, fibers, yarns, other made-up textiles … not grown, reprocessed, reused, or produced in the United States" [30]. Finally, this research will focus on TEMPER instead of SSS, as the new versions of the TEMPER require less set-up time and are likely closer in shape to future generations of shelters.

3.1 Test Program Development

There is no test standard specific to measuring the thermal performance of radiant barrier systems in temporary fabric structures for military use. In the absence of testing standards, the DoD provides guidance for the development of test programs. Figure 8 outlines the steps required to identify the requirements and tailor existing test procedures for new systems, which include characterizing the natural and operational environment in which the system will perform.

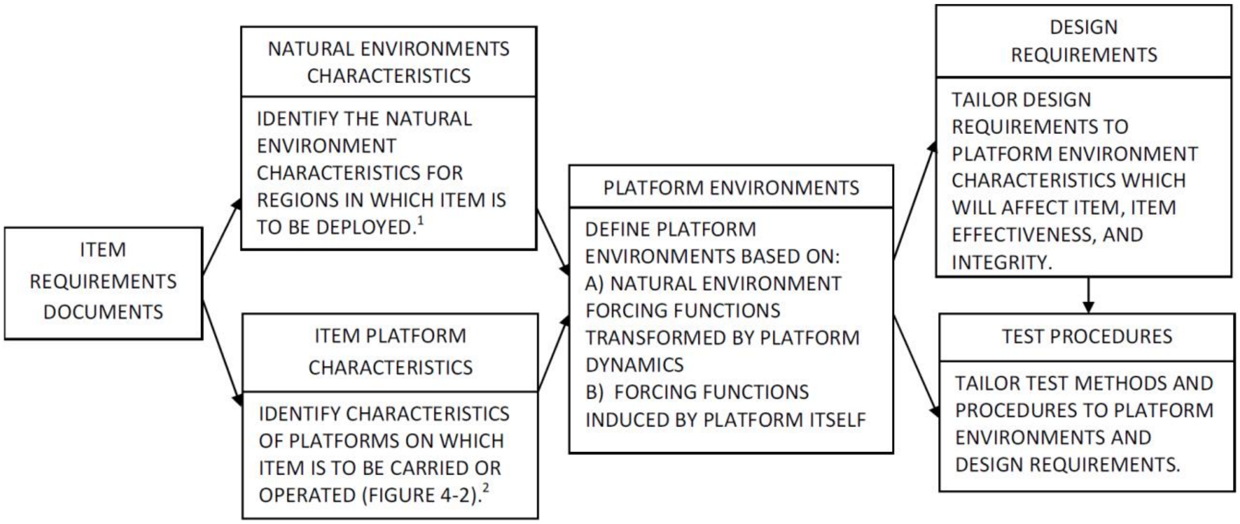

Figure 8: Schematic showing the test program tailoring process [31]

Environmental conditions vary throughout the Middle East, but overall the region is classified as hot and dry [32]. The DoD chose Kuwait as a field test location representing the extreme conditions of the Middle East to characterize the expected thermal load on the shelter, as shown in Figure 9 and Figure 10. For laboratory tests, the standard of 1120 W/m^2 and 120°F is used to represent "the hottest conditions exceeded not more than one percent of the hours in the most extreme month at the most severe locations" [31].

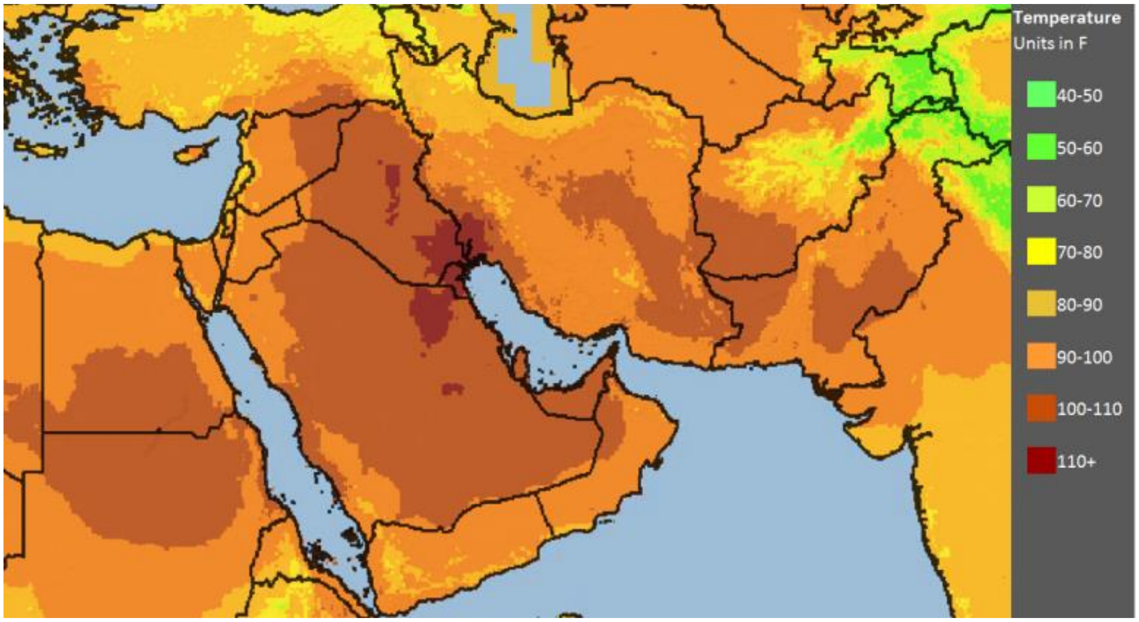

Figure 9: Map of mean maximum temperature in July for the Middle East [33]

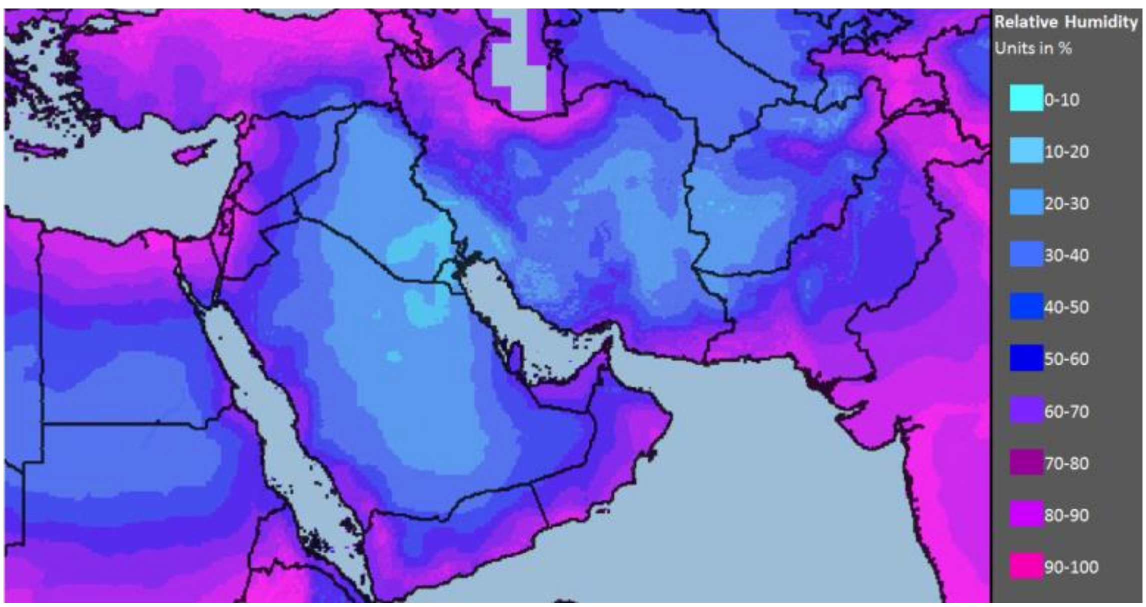

Figure 10: Map of mean maximum relative humidity in July for the Middle East [33]

The interior load is determined by each individual structure's use and the requirements of personnel and equipment inside. The standard set by Air Force operations requirements state the shelter and ECU system must provide a minimum of 30°F cooling with an ambient temperature of 110-125°F. These specifications are vague with no mention of other climatic conditions such as humidity, solar radiation, or wind speed. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) consider an interior space comfortable with the operative temperature as high as 81°F during the summer if accompanied with low relative humidity [15]. The Air Force standard of 30°F cooling with an ambient temperature of 110°F is at the threshold of comfort and will become uncomfortable as exterior temperatures approach 125°F. Furthermore, the heat produced by the equipment and personnel inside must be specified as they can significantly affect the heat load.

3.2 Operational Conditions

In addition to the environmental conditions, the operational conditions were considered. The materials used in military structures must meet specifications other than thermal performance including hydrostatic resistance, flame resistance, light weight, high strength, and a host of others. Established testing methods are used to evaluate these other requirements and are beyond the scope of this research, but must be considered when evaluating new materials. Furthermore, the material must withstand conditions encountered in transportation, storage, erection, use, and reconstitution.

3.3 Hot Box Method

The hot box method is a controlled laboratory experiment commonly used to measure the insulation value of construction materials either independently or as a system. ASTM C1363-11 provides standards regarding the construction of a hot box and the procedures for measuring and calculating the heat transfer through the test materials. The ASTM standard is written from the perspective of using insulation to prevent heat from flowing from a heated space to the cooler exterior environment, like heating a house in the winter. However, the hot box can be used "in reverse" to measure the transfer of heat from a hot environment to an interior cooled space. In this case, the metering chamber, as shown in Figure 11**,** will have a cooling element, and the opposing climatic chamber will have the heating element. Since the materials used to build the hot box are not immune from heat transfer to the surrounding ambient temperature of the environment, adjustments must be made to the calculations to account for heat loss or gain from the environment [34].

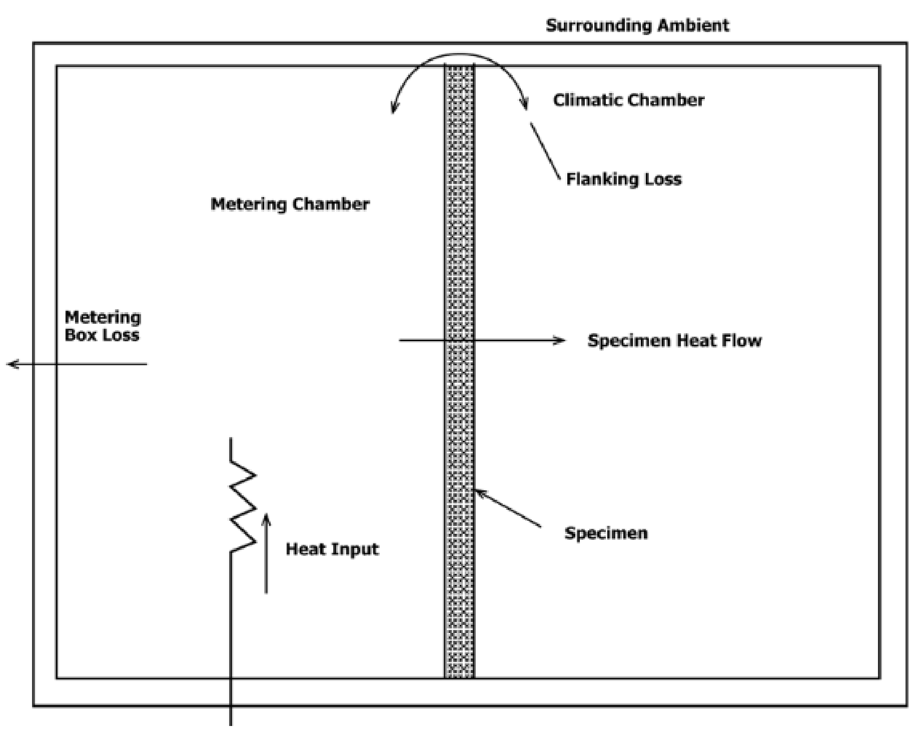

Figure 11: Hot box apparatus, ASTM C1363-11 [34]

Modification to the hot box's heat input was required to accurately evaluate the heat transfer through radiant barriers. Radiant barriers in the shelter systems are designed to reflect radiation from the sun and therefore require a specialized heat source to mimic the sun. Full-spectrum lamps were utilized to output the spectrum of wavelengths emitted by the sun that reach the Earth's surface. The specifications for the lamp are beyond the scope of ASTM C1363-11. Therefore, it was necessary to add additional guidance.

The DoD published Military Standard 810G, *Environmental Engineering Considerations and Laboratory Tests*, which addressed the simulation of solar radiation. The scope included specific types of radiation sources along with parameters for total irradiance provided in Table 2, which included spectral energy distribution, irradiance uniformity, and sensor requirements. Testing procedures were also provided.

Table 2: Spectral power distribution [31]

Spectral Region	Bandwidth (nm)	Natural Radiation (% of total)	Tolerance (% of total)		Irradiance (W/m2)	Spectral Region Irradiance (W/m2)
			Min	Max		
Ultraviolet - B	280-320	0.5	0.3	0.7	5.6	5.6
Ultraviolet - A	320-360	2.4	1.8	3	26.9	62.7
	360-400	3.2	2.4	4.4	35.8	
Visible	400-520	17.9	16.1	19.7	200.5	580.2
	520-640	16.6	14.9	18.3	185.9	
	640-800	17.3	12.8	19	193.8	
Infrared	800-3000	42.1	33.7	50.5	471.5	471.5
				Totals	1120	1120

A tent manufacturer constructed a hot box to test the thermal properties of different materials and configurations for temporary fabric structures, see Figure 12. The exterior dimensions of the hot box measure 73" wide, 128" long, and 96" high and is constructed using half-inch sheathing painted black, with two layers of two-inch foil faced foam board insulation each having an R-value of 13 (ºF x ft^2 x h/BTU). The hot box is large enough to test 64" by 132" material at a wide range of angles. It accommodates multiple layers allowing the researchers to test combinations of materials as a system with varying air gaps. The hot box is outfitted with a 6,200 BTU portable air conditioner in the metering chamber. The climatic chamber, pictured in Figure 13**,** contains the heat source, an infrared heat ballast containing three quartz halogen 2000w lamps with a box fan used to circulate the air. Thermocouples are positioned in the center of each chamber to record their respective temperatures. Additionally, thermocouples are located in each air gap between the layers of material and at the surface of the materials. Additional sensors and meters were used in conjunction with Vernier Software & Technology's "Logger Lite" software to record irradiance and air conditioning (A/C) usage in both power and runtime. Additional information about the sensors used is provided in Appendix A. Each test ran for two hours taking measurements every five seconds.

The controlled environment of the hot box is advantageous to understand the properties of the materials properties of the fabrics individually and as a system. However, the small-scale test presents limitations that must be considered. First, the aluminum tent structure is not part of the test. The material of the supporting structure acts as a thermal bridge between the layers of material, which decreases the thermal performance. Second, the final product will have seams for window, doors, and other areas where materials must be joined. The seams are not included in the test. Third, the connections from the wall-to-floor and layer-to-layer are not included.

Furthermore, the test assumes little to no air movement between layers, but this will depend on the aforementioned connections. Elements encountered in the deployed environment such as dust, rain, and humidity will likely affect the performance but cannot be captured in the test. Finally, while full-spectrum lamps mimic the sun, it does not cover the full-spectrum of wavelengths emitted by the sun. The material may perform differently with different amounts and wavelengths. The hot box method is a suitable option to choose the materials and their configuration; however, field tests in which the materials are exposed to the environment are also necessary.

Figure 12: Hot box

Figure 13: Hot box, climatic chamber (left) and metering chamber (right)

3.4 AFCEC Test Jigs

The second source of data is from test jigs created and set-up by AFCEC at Tyndall AFB, see Figure 14. The test jig's base interior dimensions are 21.5" by 75" with a peak height of 39". The side walls are constructed of plywood sheathing, 7/8" thick on the exterior and 1/2" thick on the interior with 2x4s connecting them along the perimeter. The side walls are built at approximately 46º angle and covered by the fabric materials, with each additional layer of material separated by 1.5", the actual depth of a 2x4. The total area of material exposed to the interior cavity of the jig is 2494 square inches. The interior is an open cavity with no cooling source. Like the hot box, thermocouples are placed inside the jig to measure the average temperature within the jig, at each layer of material, and the air gaps in between the materials. Tests were conducted over 24-hour periods with measurements recorded every 10 seconds. Weather data was also collected on-site via a portable weather station (PWS) and included temperature, humidity, solar radiation, and wind speed.

The jig experiment allowed for the testing of many different materials in a "real world" environment without the cost and resources required for a full-scale test. Unlike the hot box, the test jigs were exposed to elements, as they were tested outdoors at Tyndall AFB, Florida. However, this test exhibits many of the same limitation as the hot box due to the size of the test specimen. Many of the factors related to the design and construction of the shelter will not be captured within the scope of the test, such as the seams, connections, and fenestrations. Furthermore, the lack of a cooling source creates additional complexity. At the beginning of the test, the interior temperature is cooler than the ambient temperature. However, as the sun rises, the heat builds up inside the jig, and the interior space becomes hotter than the ambient temperature like a car sitting in a parking lot on a hot day. Once the interior temperature is greater than the ambient temperature, the conductive heat flow reverses. However, because fabrics have negligible thermal mass and low emissivity, the main source of heat transfer will continue to be solar radiation flowing into the jig.

Figure 14: AFCEC's test jigs at Tyndall AFB

3.5 AFCEC Full-Scale Tests

The final source of data is from a full-scale test performed by AFCEC in a variety of locations around the world including: Ali Al Salem Air Base**,** Kuwait; Tyndall AFB, Florida; Holloman AFB, New Mexico; and Anderson AFB, Guam. These full-scale tests included TEMPER and SSS tents with different combinations of liners, skins, and flies. Shelters were erected approximately 12 feet apart and shared a single ECU. Weather data including temperature, humidity, solar radiation, and wind speed was collected on-site. Inside the structure, thermocouples were used to measure the ambient temperature along with the temperature at the surface of each material and the temperature of the air gaps between the materials. The 48 sensors shown in Figure 15 recorded data every 10 seconds over a 24-hour test period. The thermal performances of the structures were measured as a function of the ECU usage in both power and runtime.

The main advantage of the full-scale test was testing the complete system as a whole in the actual environment in which these structures are expected to perform; the only difference being the absence of people and equipment occupying the space. This test accounts for all fenestrations, thermal bridging caused by the structure, and infiltration. However, there are some limitations to the test. AFCEC tested the structures as a system of two shelters connected by one ECU and associated duct work. At times, different configurations on each of the structures were tested. While the temperature data is still useful, noise is introduced to the data collected from the ECU usage. Additionally, if only one shelter or an odd number of shelters was needed for the operation, the efficiency may decrease. Finally, because the structures are located close together, shading and radiation reflecting may occur.

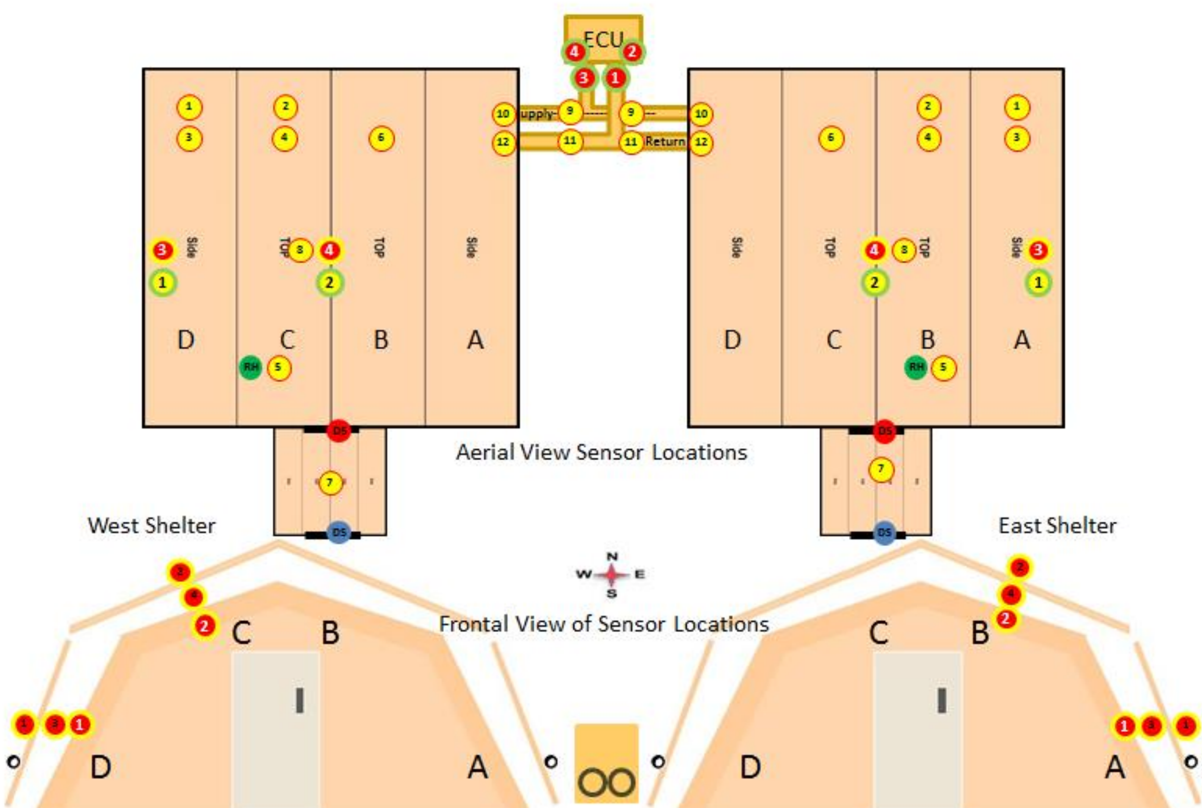

Figure 15: TEMPER with sensor locations

3.6 Fabric Material Information

Materials were tested from three manufacturers. Each company integrates a layer of radiant barrier into their materials and claims enhanced thermal properties. However, much of the material property data is proprietary and closely held within the companies. Some information is available in the product data sheets summarized in Appendix B. The data sheets provide some useful information on the individual properties of the material, but testing is required to see how the different materials interact with each other in a multilayer system.

3.7 Design of Experiments

A Design of Experiments was developed to systematically test all the different combinations of materials to determine the optimal material configuration. Materials are classified as either radiant barrier or standard; the generic term “radiant barrier” was used for all manufacturer’s materials as the purpose of this study was to test the effects of radiant barriers, not to compare the material performance of the specific products. All combinations are shown in Table 3. Each configuration must have a skin layer but can also have an inner liner and/or outer fly. To test the effects of the direction of the radiant barrier, the liner could be faced inward or outward. This allowed for 24 possible combinations for the small shelters. Due to limited resources, only select combinations were tested in the hot box and test jigs.

Additionally, variations of ventilated fly layers were tested in the experiments. In the hot box experiments, a non-radiant barrier mesh fly with approximately 72% shading and therefore 28% light transmission was tested. In the test jig experiment, a combination fly with mesh sides and a radiant barrier top was tested. These flies added an additional component of solid versus ventilated fly and the potential tradeoff of convective cooling compared to the isolative value of still air trapped between layers.

Table 3: Design of Experiments with up to three layers

Skin	Liner	Fly
Standard Skin	No Liner	No Fly
		Standard Fly
		Fly with Radiant Barrier
	Standard Liner	No Fly
		Standard Fly
		Fly with Radiant Barrier
	Liner with Radiant Barrier	No Fly
		Standard Fly
		Fly with Radiant Barrier
	Liner with Radiant Barrier reversed	No Fly
		Standard Fly
		Fly with Radiant Barrier
Skin with Radiant Barrier	No Liner	No Fly
		Standard Fly
		Fly with Radiant Barrier
	Standard Liner	No Fly
		Standard Fly
		Fly with Radiant Barrier
	Liner with Radiant Barrier	No Fly
		Standard Fly
		Fly with Radiant Barrier
	Liner with Radiant Barrier reversed	No Fly
		Standard Fly
		Fly with Radiant Barrier

3.8 Defining Variables

The climatic data are the independent variables and are defined as:

- Temperature in degrees Fahrenheit
- Humidity as a percent ranging from zero to one-hundred
- Solar Radiation in watts per square meter
- Wind Speed in miles per hour
- Wind Direction based off of 360 degree compass

The dependent variables and are defined as:

- Surface temperatures of material in degrees Fahrenheit of the fly, skin, and liner
- Gap temperature in degrees Fahrenheit of the outside air gap (between fly and skin) and the inside air gap (between the skin and the liner)
- Interior temperature of structure in degrees Fahrenheit

IV. Results

4.1 Hot Box Experiment

The goal of the hot box experiment was to provide insight into the basic heat transfers occurring through the layers, thus giving a better understanding of how the system of layers interact with each other. Specifically, the effect of number of layers, number of radiant barriers, and direction of radiant barriers were observed. The advantage of the hot box is the controlled test environment, which minimized variation both within the tests and between tests which is not possible in successive in-situ testing.

The design of experiments for the hot box includes two different flies, three different skins, and four different liners, plus the option to have no liner and/or no fly. This resulted in 45 different possible combinations. However, because the purpose of this research is not to test the performance of different manufacturers of fabrics, but rather the radiant barrier technology, the materials used were classified as either radiant barrier or non-radiant barrier materials (standard). For the flies, the non-radiant barrier material was mesh for increased ventilation. With this classification, and all two-layer configurations only consisting of skin and liner, there are only nine different possible configurations as shown in Figure 16. More combinations are possible if the placement of the radiant barrier within the system is considered, but this issue is addressed separately later in this chapter. Of the nine possible configurations, eight different configurations were tested. In total, five tests were conducted with only one layer, the skin. Seven tests were conducted using two layers, the skin and liner. Four tests were conducted using all three layers. A breakout of the test conducted with air conditioning (A/C) is provided in Figure 16.

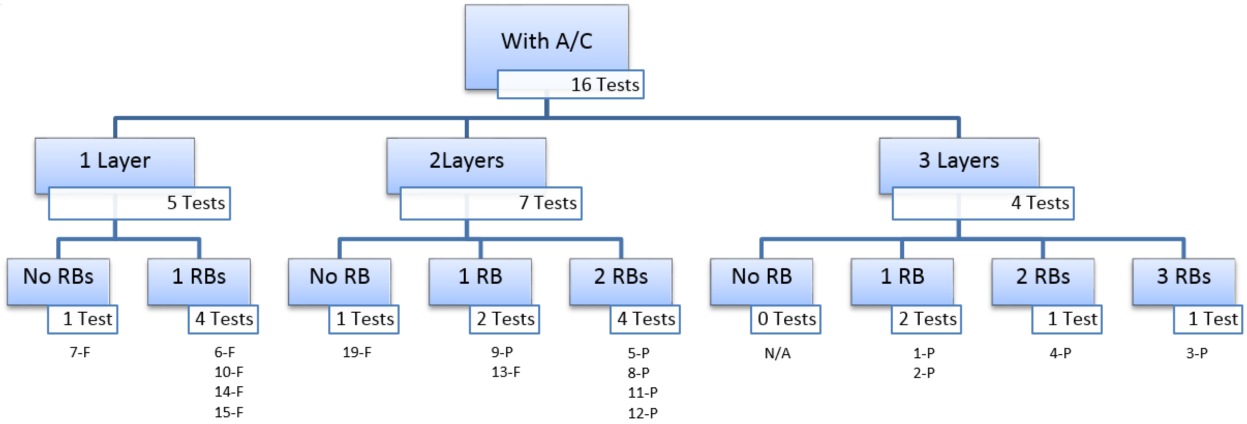

Figure 16: Tests conducted by number of layers and radiant barriers

<u>4.1.1 Test Procedure.</u>

All tests were set-up and conducted by the same person to minimize variations. The hot box was opened to equalize the temperature between the building housing the hot box and the interior of the hot box. The 6991 in^2 layers of fabric were set at angles consistent with the TEMPER wall and ceiling, and fastened to the walls with hook and look type fasteners. Each fabric layer was installed via hook and loop fasteners integrated into the perimeter of the material to hook and loop fastener straps lining the interior of the hot box. Skin temperature sensors were installed in the center of the wall panel on the exterior side of each layer. Once the temperatures in the hot box on either side of the fabric reached 71±2 ºF, the experiment commenced by turning on the heat lamps, fan, and data logger. Each test ran for two hours.

4.1.2 Data Collected.

A tent manufacturer provided data collected on all experiments conducted in their hot box apparatus. As described in the methodology section, data was collected every five seconds for time, irradiance, ambient "outside" temperature of the climatic chamber, ambient "inside" temperature of the metering chamber, and the skin temperature of each layer, as well as the air conditioner's response measured in real power consumed, potential power, current, and apparent power. The data from each two-hour test was logged by Vernier Software & Technology's "Logger Lite" software, then saved as an Excel sheet. All tests were then combined into one file in the statistical software JMP for statistical analysis.

In total, 19 tests were conducted. Test 16, 17, and 18 were excluded from this section of analysis as they did not use A/C, but they are considered later in this chapter. The remaining 16 tests resulted in 32 hours of data collected every five seconds for 11 different parameters, equaling 300,690 data points. A summary of the results are provided in Table 4, and an example test result is provided in Appendix C.

In Table 4, specific product names were replaced with letters for anonymity, and the red cells indicate radiant barriers. The controlled variables included the irradiance provided by the climate chamber, which averaged 480.07 W/m^2 but the average ranged from 365.86 to 523.98 W/m^2. The A/C unit was set to 72°F in the metering chamber, but the actual interior temperature varied for each configuration. Each test lasted two hours. The external temperature averaged $108.87°F$ but the average ranged from $104.69°F$ to $116.22°F$. The surface temperature of each fabric layer, A/C runtime, and A/C power consumption depended on the configuration.

Table 4: Hot box test summary

Test Number		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Outer Layer - Fly		A	A	B	A															
Middle Layer - Skin		C	C	B	B	B	B	C	B	C	B	B	D	B	D	D	D	B	C	C
Inner Layer - Liner		E	F	E	E	E			E	E		E*	E	G						H
Number of layers		3	3	3	3	2	1	1	2	2	1	2	2	2	1	1	1	1	1	2
Number of RBs		1	1	3	2	2	1	0	2	1	1	2	2	1	1	1	1	1	0	0
Average Irradiance	W/m²	466.44	449.91	444.45	459.73	490.26	365.86	507.45	467.97	470.77	499.58	507.72	504.31	508.89	476.97	505.61	516.16	523.98	472.68	482.65
Avg External Temp	°F	110.85	110.96	116.22	111.03	108.55	107.70	107.57	107.59	107.01	111.36	107.70	107.50	107.88	104.69	109.75	108.61	109.93	107.23	106.44
Average Fly Surface Temp	°F	116.40	116.26	136.16	116.48	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Average Skin Surface Temp	°F	123.79	120.97	128.88	118.38	122.83	119.42	116.31	126.87	130.89	120.98	127.50	125.97	127.85	110.60	115.45	123.41	123.16	123.82	121.34
Average Liner Surface Temp	°F	96.78	105.30	100.12	95.38	99.45	N/A	N/A	99.11	102.28	N/A	115.60	98.60	101.15	N/A	N/A	N/A	N/A	N/A	112.03
Average Internal Temp	°F	72.02	72.69	73.63	72.01	72.57	86.97	89.86	71.87	72.12	89.05	72.69	72.10	79.81	84.80	88.34	99.23	103.29	106.07	75.16
Test Time	hr	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Area	in²	6991	6991	6991	6991	6991	6991	6991	6991	6991	6991	6991	6991	6991	6991	6991	6991	6991	6991	6991
A/C Consumption	kWh	0.883	1.262	1.243	0.653	1.183	1.612	1.730	1.050	1.067	1.656	1.225	1.125	1.615	1.657	1.671	0.000	0.000	0.000	1.414
A/C Runtime	hr	1.16	1.63	1.53	0.89	1.53	1.94	1.96	1.37	1.40	1.94	1.56	1.41	1.93	1.92	1.93	0.00	0.00	0.00	1.80

4.1.3 Measure of Performance.

The three dependent variables measured to determine the thermal performance were A/C runtime, A/C power consumption, and internal temperature. In theory, the A/C runtime and A/C power consumption variables should be highly correlated as the A/C will only run when it is consuming power and the A/C should consume power at a fairly constant rate. The calculated adjusted Pearson's correlation coefficient between the resulting A/C runtimes and A/C power consumption of the 16 experiments is 0.979, see Appendix D. Because the two variables are highly correlated, either one may be used to indicate system performance, A/C runtime was used. In addition, the interior temperature was also used to define success of a system as a binary pass or fail. If the average interior temperature remained below $74°F$ (with a set point of $72°F$) then the system passed, if greater than or equal to $74°F$ (with a set point of $72°F$) the system failed. The $74°F$ was a natural separation in the data, see Appendix E, and indicated that the A/C could not meet the demand; if the test were continued longer than two hours, the A/C would run constantly while the interior temperature would continue to increase past the set point.

A direct comparison of tests using any performance metric may be misleading as the independent variables, irradiance and exterior temperature, vary for each test. This variation is due to the fastidious nature of the homemade hot box apparatus. The effects of these inconsistencies were minimized by the increased number of tests performed in each category tested. The distribution of irradiance and exterior temperature is shown in Figure 17. The most influential variable, external temperature, generally increases with increased number of layers and number of radiant barriers. Any efficiencies gained by increasing the number of layers or radiant barriers are then assumed to be valid as the actual higher exterior temperature would otherwise result in an increased interior temperature. The variance in irradiation is less concerning as literature review from radiant barriers systems in attics suggests that the solar radiation does not have a significant effect on the performance of radiant barriers [1]. A Tukey analysis for the comparison on means confirmed that two groups of tests existed that were not significantly different in terms of both irradiance and exterior temperature; one group of Tests 7, 11, 12, and 13, and another group of Test 8 and 9. This analysis is available in Appendix F.

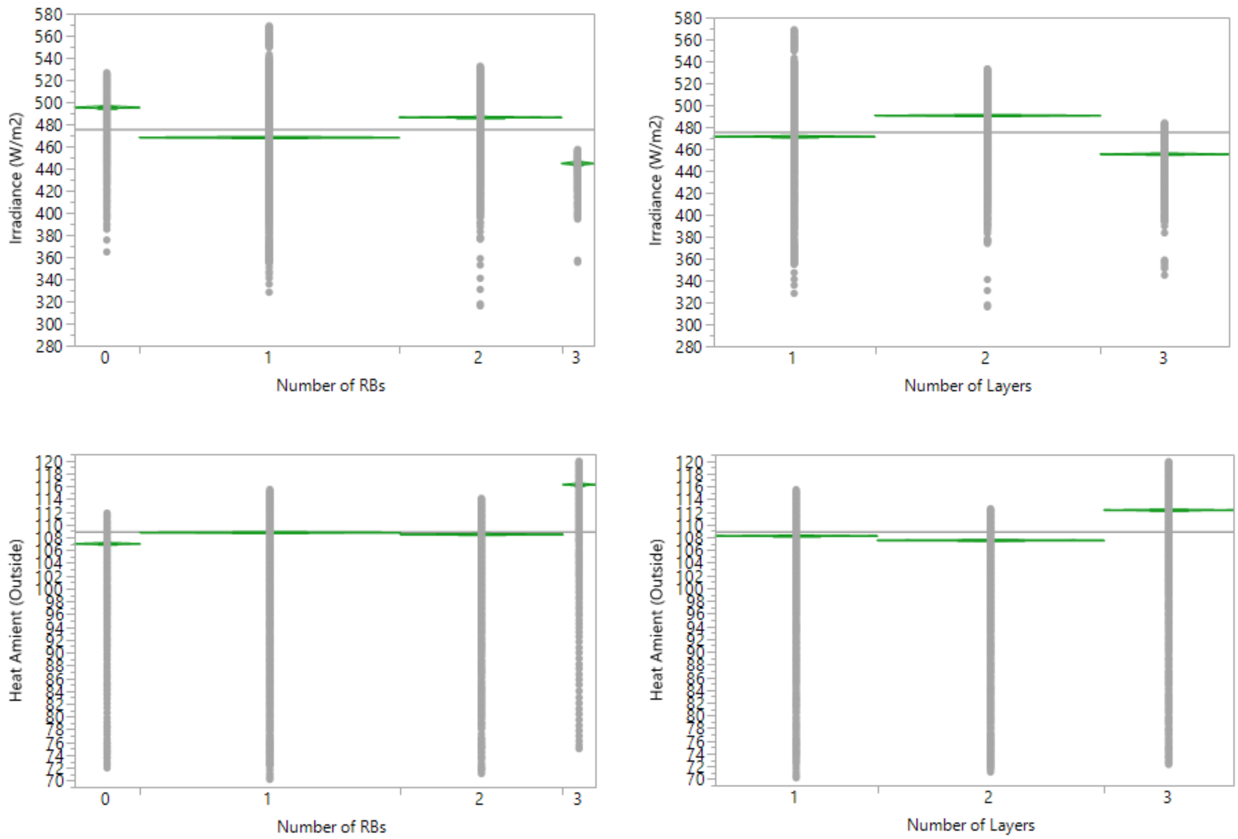

Figure 17: Irradiance and exterior temp by number of radiant barriers and layers

4.1.4 Effect of Number of Layers and Radiant Barriers.

Using the interior temperature below 74°F as a definition of success, the following observations were made:

1. Every experiment with only one layer failed
2. 5 of the 7 two-layer experiments passed
3. Every three-layer experiment passed

The number of layers appeared to be the primary factor determining the success of the tests; however, there are a few interesting results which are more apparent when viewing Figure 16. Test 9 and Test 13 both contained two layers and one radiant barrier; however, Test 9 passed with an average internal temperature of 72.12°F while Test 13 failed with an internal temperature of 79.81°F. The differences between the tests include the manufacturers of materials and the placement of the radiant barrier. Test 9's radiant barrier was the interior liner while and Test 13's radiant barrier was the outer skin layer, suggesting that the radiant barrier is more effective when placed on the inner layers. However, no conclusions can be made from two data points, so the effects on A/C runtime will be considered next.

The A/C runtime is plotted against the number of layers in Figure 18, and against the number of radiant barriers in Figure 19; full ANOVA testing is provided in Appendix G. In Figure 18**,** the standard deviation within each layer is high, but the downward sloping best-fit line suggests the increased number of layers decreases the A/C runtime. This aligns with Observation 1 above and suggests the increased number of layers results in increased thermal performance of the system. Next, Figure 19 shows a similar outcome, the increased number of radiant barriers correlates with a decreased A/C runtime, except in the one test with three radiant barriers. However, the high standard deviation and the small sample size leaves doubt and emphasizes the need for further tests.

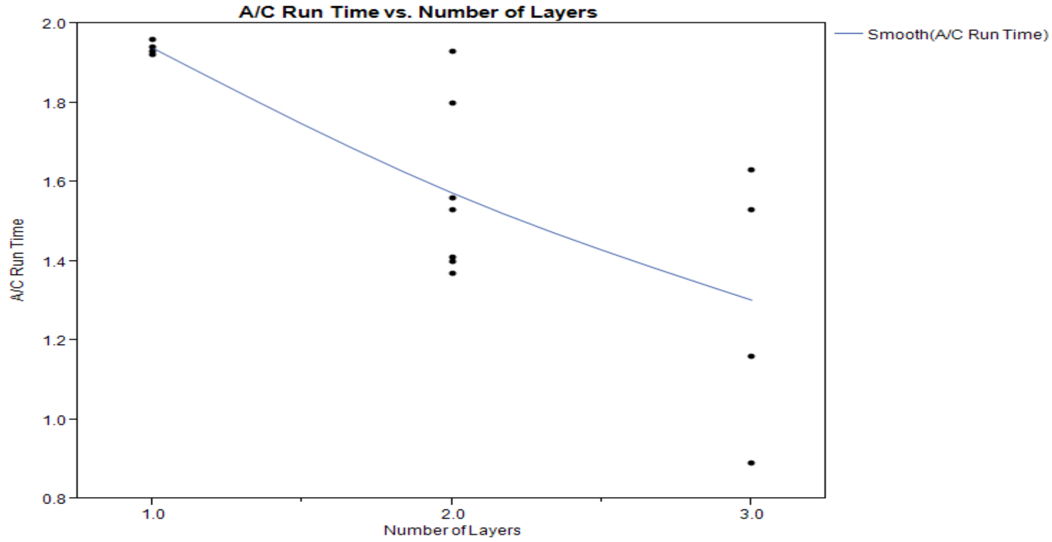

Figure 18: A/C runtime vs. number of layers

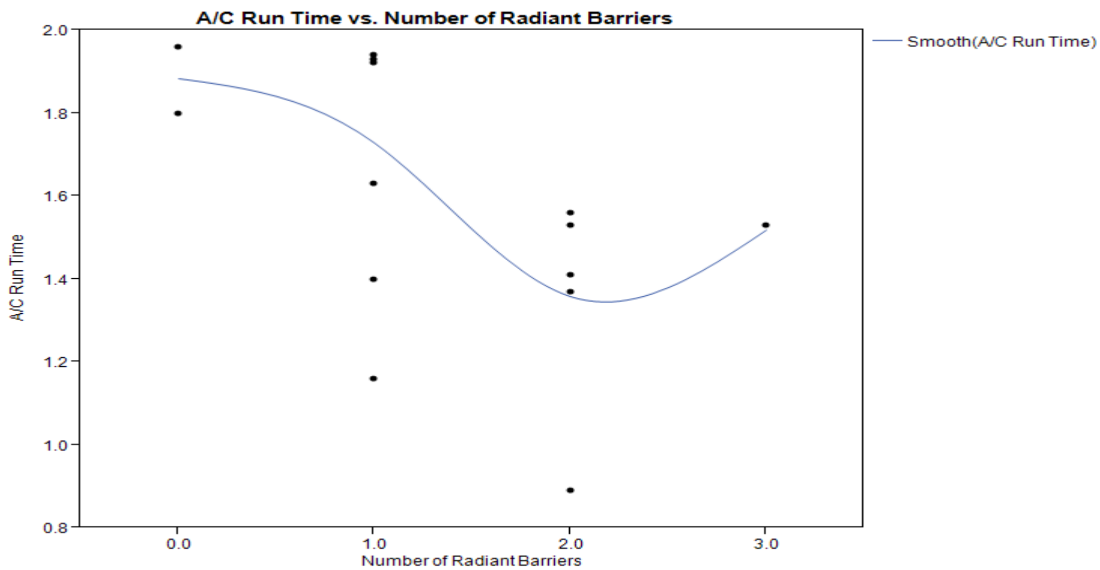

Figure 19: A/C runtime vs. number of radiant barriers

4.1.5 Interaction of Number of Layers and Number of Radiant Barriers.

Both the number of layers and number of radiant barriers appear to affect thermal performance as stated in the previous section. Table 5 shows the two-way ANOVA comparing the effect of each variable to the resulting runtime of the A/C. This table shows that the number of layers is the main effect. However, the single test conducted with three layers and three radiant barriers may be skewing the results.

Table 5: Two-way analysis of number of layers and radiant barriers

Possible test configurations		Number of Radiant Barriers 0	1	2	3	Average A/C runtime (hrs)
Number of Layers	1	1.96	1.93			1.95
	2	1.80	1.67	1.47		1.64
	3	-	1.40	0.89	1.53	1.27
	Average A/C runtime (hrs)	1.88	1.66	1.18	1.53	

4.1.6 Effect of Radiant Barrier Placement.

The next question is the importance of radiant barrier placement, which is not clearly indicated by the pass/fail interior temperature metric. This information is more difficult to discern as there are many combinations of possible radiant barrier placements. To simplify the analysis, single-layer tests were excluded, as there is no inner and outer layer. For two-layer systems, there are three possible configurations with at least one radiant barrier, all of which were tested. For three-layer systems, there are seven possible configurations; the only three tested were a radiant barrier liner, a radiant barrier skin and fly, and radiant barriers for all three layers. In Figure 20, the different configurations were graphed in descending order of average

A/C runtime; “r” denotes radiant barrier and “x” denotes non-radiant barrier for the liner, skin, and fly, in that order. Figure 20 indicates the tests with an outermost layer having a radiant barrier performed the worst. However, because the tests with fly “x” is mesh instead of a solid material, this could be interpreted as the mesh fly performing better than the radiant barrier fly, not a non-radiant barrier fly performing better than a radiant barrier fly. While this was not predicted by the researcher, it suggests that ventilation of the fly layer is more important than a radiant barrier.

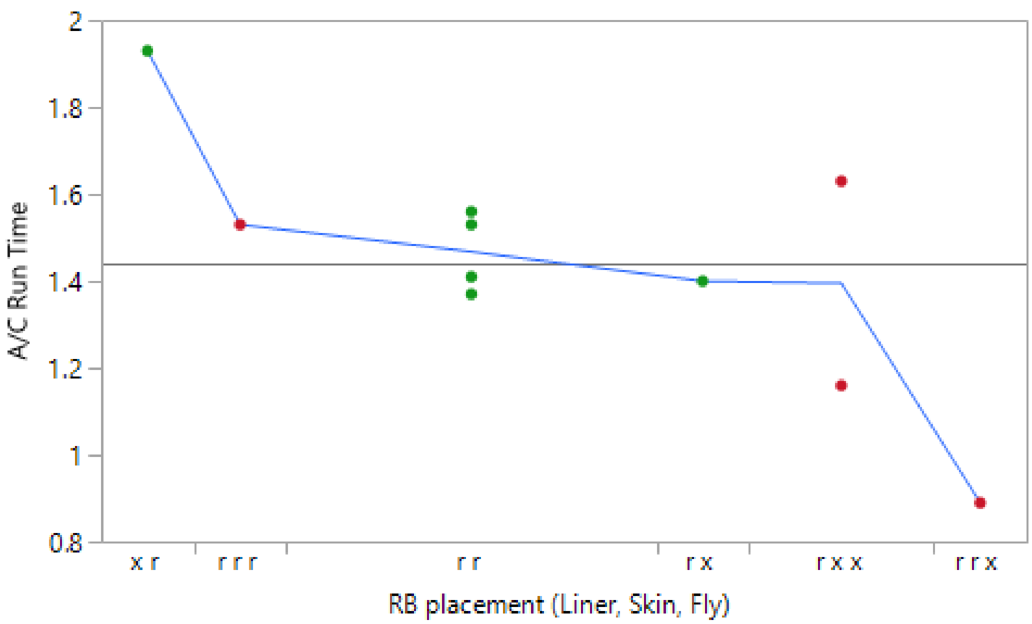

Figure 20: A/C runtime vs. radiant barrier placement

4.1.7 Effect of Direction of Radiant Barrier Liner.

The effects of the direction of a radiant barrier liner was observed in Test 8 and Test 11. Each test utilized the same radiant barrier skin and the same radiant barrier liner, except the radiant barrier liner in Test 8 faced outward while the radiant barrier in Test 11 faced inward. These tests are not significantly different in terms of the most influential independent variable temperature, but the average irradiance is almost 40 W/m^2 or 8.5% higher for Test 11. The A/C runtime of Test 8 was 11.4 minutes shorter (13.6%) over the two-hour test. While a conclusion cannot be made from two data points, the results suggest that facing the radiant barrier outward is more effective. The direction of the radiant barrier was tested again using the test jigs; results are provided later in this chapter.

4.1.8 Performance of Mesh Fly versus Radiant Barrier Fly.

The series of tests performed used two different fly materials. One was a radiant barrier fly while the other was non-radiant barrier mesh material. The mesh fly allowed for ventilation of the outermost layer. Four tests were conducted using a fly layer, but only Test 3 and Test 4 used the same skin and liner, allowing for direct comparison of the flys. The A/C in Test 4 only ran for 0.89 hours compared to Test 3's A/C running for 1.53 hours. However, these tests cannot be fairly compared as the average exterior temperature of Test 3 was 5.19°F higher. Therefore, more tests with less variation would be required to determine which fly performs better.

4.1.9 Characteristics of Best Performing Configuration.

As shown in Figure 21, Test 4 was by far the best performing configuration of the 16 tested. The configuration consisted of three layers with the radiant barrier skin and liner. The A/C ran for 0.89 hours consuming 0.663 kWh, which was 26.1% more efficient than the next best test, Test 1. Test 8 was the best performing two-layer test. The configuration consisted of both the skin and liners being radiant barriers. The A/C ran for 1.37 hours consuming 1.05 kWh, which is 36.9% less efficient than the best three-layer test. This test aligns with all the previous observations that increased number of layers, having a mesh fly outmost layer instead of a solid radiant barrier, and facing radiant barriers outward results in the best performance. However, this data must be interpreted with caution due to the inconsistencies of the testing conditions.

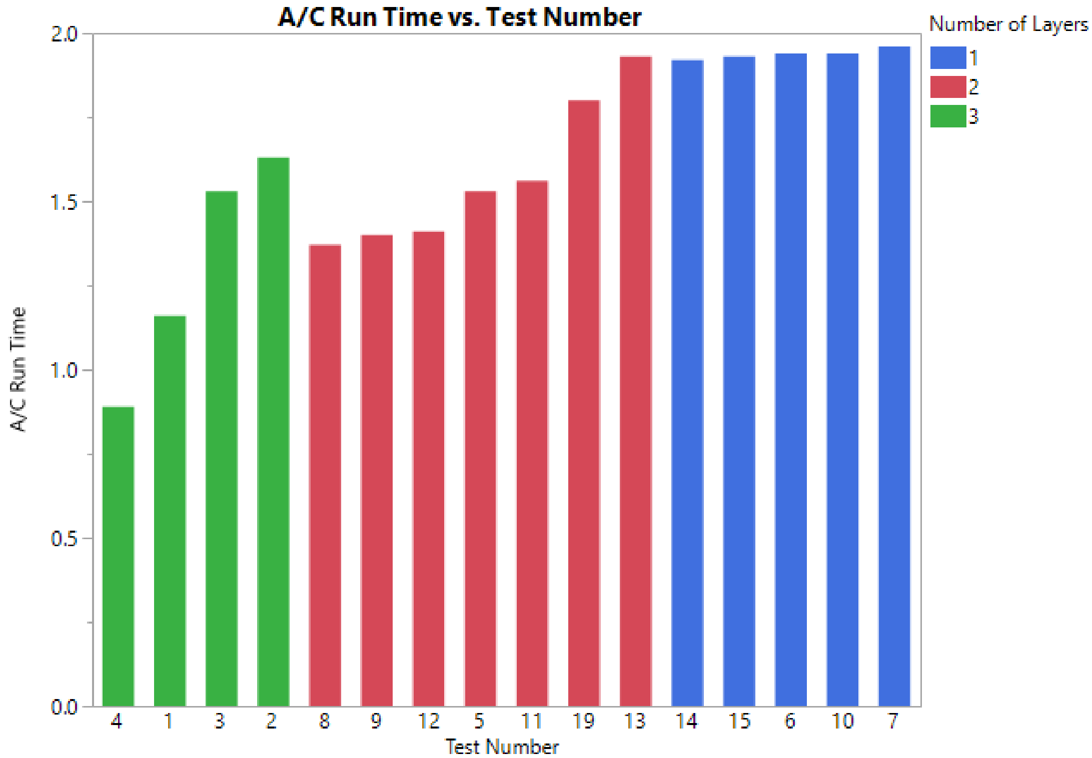

Figure 21: Comparison of A/C runtime by test

4.1.10 Hot Box Tests without A/C.

Three tests previously excluded from the analysis were Tests 16, 17, and 18 because they did not use A/C. These tests are shown in Table 6; however, the measure of performance cannot be the same. A direct comparison of the internal temperatures could be used if the test conditions were identical; however, the independent variables varied between each test. Therefore, a difference in temperatures between the exterior and interior was used to compare the tests. The best performing configuration will have the highest difference of temperatures as it will resist the transfer of heat the best. This measurement of performance assumes a constant resistance to heat transfer across the exterior temperature range; while this assumption does not hold true for large difference in temperatures, the difference of exterior temperatures is this case varies less than $3°F$ so any error introduced is assumed to be negligible.

The average exterior temperature remained fairly constant for the three tests conducted, but the interior temperatures varied significantly. The internal temperature of Test 16 was $9.38°F$ cooler than the exterior, Test 17 was $6.63°F$ cooler, and Test 18 was $1.16°F$ cooler, suggesting that Test 16 performed the best followed by Test 17, then Test 18. The result was not surprising as Test 18's skin was the only non-radiant barrier. With the small sample size and large variation of irradiance, further testing would be required to confirm the suggestion that radiant barriers for one-layer configurations perform the best. This assertion is tested again in the jig tests later in this chapter.

Table 6: Hot box tests without A/C

Test Number		16	17	18
Date		20160401	20160401	20160401
Outer Layer - Fly				
Middle Layer - Skin		D	B	C
Inner Layer - Liner				
Number of layers		1	1	1
Number of RBs		1	1	0
Average Irradiance	W/m^2	516.16	523.98	472.68
Avg External Temp	°F	108.61	109.93	107.23
Average Fly Surface Temp	°F	N/A	N/A	N/A
Average Skin Surface Temp	°F	123.41	123.16	123.82
Average Liner Surface Temp	°F	N/A	N/A	N/A
Average Internal Temp	°F	99.23	103.29	106.07
Test Time	hr	2	2	2
Area	in^2	6991	6991	6991
A/C Consumption	kWh	0.000	0.000	0.000
A/C Runtime	hr	0.00	0.00	0.00

4.1.11 Limitations.

This analysis does not address the different material properties associated with the different manufacturers; it simply categorizes the materials as radiant barrier or non-radiant barrier to explore the effects of the number of layers, number of radiant barriers, and their placement within the system. This assumption may oversimplify the data, as some manufacturer's radiant barriers may perform better than others; however, the purpose of this study is not to identify which manufacturer has the best radiant barrier. Further experiments should exhaust all configurations of one manufacturer to reduce the variability introduced by different materials with different properties.

Next, the hot box method may not be the most suitable test for the thermal characteristics of a single layer of material. Alternatively, ASTM C518-15 should be considered. While the hot box method is designed to evaluate a building system, the heat flow meter apparatus is designed to evaluate a single material. This method may be used to determine the best product for each layer, and then the hot box can be used to test the thermal performance of the overall system. Furthermore, the relatively short two-hour test with a constant high temperature and high exposure to solar radiation aligns closer to an actinic effect test used to accelerate the degradation of a material exposed to sunlight [31]. A more appropriate test would be 24-hours long and mimic the fluctuation in temperature and solar radiation that occur throughout the day [31].

The data analyzed was acquired from a fabric shelter manufacturer, who built the hot box apparatus and performed the tests. No data was provided on the environmental conditions of the room in which the tests were conducted. Changes in room temperature and humidity between experiments may affect the results. Furthermore, when multiple test were performed in one day, there may be bias introduced as the hot box absorbs the heat from the first test and radiates that heat into the second test. Ideally, there would be adequate time between each test for the hot box temperature to completely equalize with the constant room temperature. This also applies to the A/C unit as the efficiency of the unit likely changes from one test to the next depending on how much time it sits idle between tests.

When performing tests, issues with the layout and construction of the hot box were discovered, which likely affect the results. First, the lamp placement of the full-spectrum bulbs did not provide for even coverage of the test material. Consequently, temperature and solar irradiance on the outer layer varied depending on the proximity to the lamp. Temperature differences of greater than 20°F were observed over the outermost layer. Furthermore, there was no way to control or monitor humidity within the test. While the humidity likely did not fluctuate significantly in the conditioned space where the test was performed, any fluctuations were not captured and cannot be incorporated into the analysis. Finally, the fan used to circulate the heat in the climatic chamber was not measured for wind speed or direction. The fan was set consistently for each test, but in the absence of measured wind speed and direction, the effects of the wind were not incorporated into the analysis.

Finally, the small-scale of the material may experience less air movement within the air space due to convection currents, possibly resulting in more favorable results. While the set-up of the hot box was not optimal, the data is still useful, as the testing methods were consistent. Therefore, the test configurations can be compared against each other, but a direct measure of performance as heat flux will not be accurate.

4.1.12 Hot Box Summary.

Further research is required to substantiate the results of the hot box experiment. However, the available data indicates that the number of layers is positively related to the thermal performance of the temporary fabric shelters. Next, the optimum number of radiant barriers may be two and radiant barriers should be faced outwards. Further research should test a system with every combination from only one manufacturer to eliminate the bias created by using materials from different manufacturers with different material properties. Any additional testing should be conducted in a professionally manufactured and calibrated hot box apparatus.

4.2 Test Jig Experiment

The Air Force Civil Engineer Center (AFCEC) designed the test jig experiment as a defender-challenger scenario in which different configurations and different manufacturers' products were tested side-by-side for a period of time and the highest performing jig remained, while the lesser performing challengers were replaced by different products or configurations. By process of elimination, the best performing jigs are identified and can be compared against new technologies as they emerge. This type of test allows direct comparison of the different jigs under nearly identical climatic conditions within each test. However, it does not allow for comparison of jigs between different test periods. Comparing configurations between different tests was more complex because the climatic conditions are constantly changing and no two days are exactly the same.

This analysis focused on eight different tests conducted from 5 August 2015 to 21 March 2016, see Table 7. Test 3 and 4 were excluded as they tested a homemade fly that was later replaced by a manufacturer's version of the same fly tested in Tests 9 and 10. In total, eight tests of two jigs were analyzed in this research. Data from two test jigs, Jig A and Jig E, were compared for each of the eight tests. The only difference between the material configurations of A and E was that E utilized a standard skin while A utilized a skin with a radiant barrier technology. This allowed A and E to be compared directly as they sat side-by-side under identical climatic conditions within each tests. This analysis also compared jigs from different test. It is important to note that the radiant barrier technology tested in the jigs are different products from the previous hot box tests.

Table 7: Test jig experiments conducted

			Liner			Skin		Fly	
Test	Test Dates		Radiant Barrier (RB)	Standard (Std)	RB Reversed	Std	RB	Std	RB with Mesh
1	5-Aug-15	12-Aug-15				E	A		
2	13-Aug-15	17-Aug-15	X			E	A		
5	2-Sep-15	22-Sep-15		X		E	A	X	
6	22-Sep-15	4-Dec-15		X		E	A		
7	4-Dec-15	18-Dec-15		X		E	A		X
8	21-Dec-15	29-Feb-16	X			E	A		X
9	29-Feb-16	7-Mar-15			X	E	A		X
10	7-Mar-15	21-Mar-16				E	A		X

4.2.1 Test Procedure.

The test jigs were created and set-up by AFCEC at Tyndall Air Force Base (AFB). The test jig's base interior dimensions are 21.5" by 75" with a peak height of 39". The side walls are constructed of plywood sheathing, 7/8" thick on the exterior and 1/2" thick on the interior with 2x4s connecting them along the perimeter. The side walls are built at approximately 46º angle and covered by the fabric materials, with each additional layer of material separated by 1.5", the actual depth of a 2x4. The total area of material exposed to the interior cavity of the jig is 2494 square inches. The interior is an open cavity with no cooling source. Like the hot box, thermocouples are placed inside the jig to measure the average temperature within the jig, at each layer of material, and the air gaps in between the materials. Tests were conducted over 24-hour periods with measurements recorded every 10 seconds. Weather data was also collected on-site via a portable weather station (PWS) and included temperature, humidity, solar radiation, and wind speed and direction.

4.2.2 Data Collected.

Data was collected simultaneously from the jigs and a PWS and recorded using LabVIEW® by National Instruments. Separate csv files for the PWS data and jig data were created for each test day, with recordings taken every ten seconds. The MATLAB® code in Appendix H written by 2d Lt Noah Blach condensed the 10 second data in each file into hourly averages, then exported all test days into one Excel file. Then, the Excel file was loaded into JMP® for statistical analysis.

A total of 213 days or 5112 hours of data were collected; however, not all of the data was usable. Data was excluded depending on the physical conditions on-site. At the conclusion of each test, the jig was dismantled and rebuild for the next test. During this time, the data continued to log; using notes from the test administrator, these windows were identified and excluded. Also, identified anomalies like a lightning strike during Test 1, which disabled an Ethernet switch and disrupted data collection caused a loss of data on August 8th and 9th. Next, MATLAB code was used to clean the data.

The MATLAB code excluded data that was incomplete; if missing data from any hour totaled more than one minute, the entire hour was excluded. This ensured the average hourly data from the two separate systems, the jigs and portable weather station (PWS), were reasonably aligned. Additional screening of the data occurred in JMP. The sensors outputted error codes in the 4000s; to remove these error codes from the data set, each column was range checked to ensure all value fell within a set range; otherwise the data points were omitted. Through the process of cleaning the data, 958 hours or 18.7% were excluded, leaving a total of 4154 hours.

Once error codes were removed from the data, further exclusion of data was necessary. The data was scanned for missing values; 62 hours of the 4154 total hours were excluded for missing values. The missing information was most likely due to sensor malfunctions or disconnection. These types of errors accounted for less than 1.5% of the total data after cleaning.

Next, nighttime hours were excluded as the sun and consequently solar radiation was not present. Radiant barriers were specifically designed to reflect solar radiation so testing their performance at night obscures the data and could negate their potential effectiveness. A precedence for the separation of daylight and nighttime hours for analysis was based off the Tennessee Valley Authority's testing of radiant barriers [14]. For this research, "daylight hours" were defined as the average solar radiation for any hour greater than 20 W/m^2. Only 45.1%, were considered daylight hours.

As indicated in Table 7, the length of each test varied. This variation was due to the availability of new products to test from the manufacturers and manpower availability at the AFCEC site required to manage and reconfigure the test jigs. Figure 22 shows the total amount of hours of data collected for each test. In a general sense, the longer the test period equates to more data collected, resulting in a larger range of climatic variables, therefore providing a more holistic performance of the jigs. Test 1 and Test 2 had the least amount of collected, but still provided 94 hours of usable data, 47 of which were during hours of daylight.

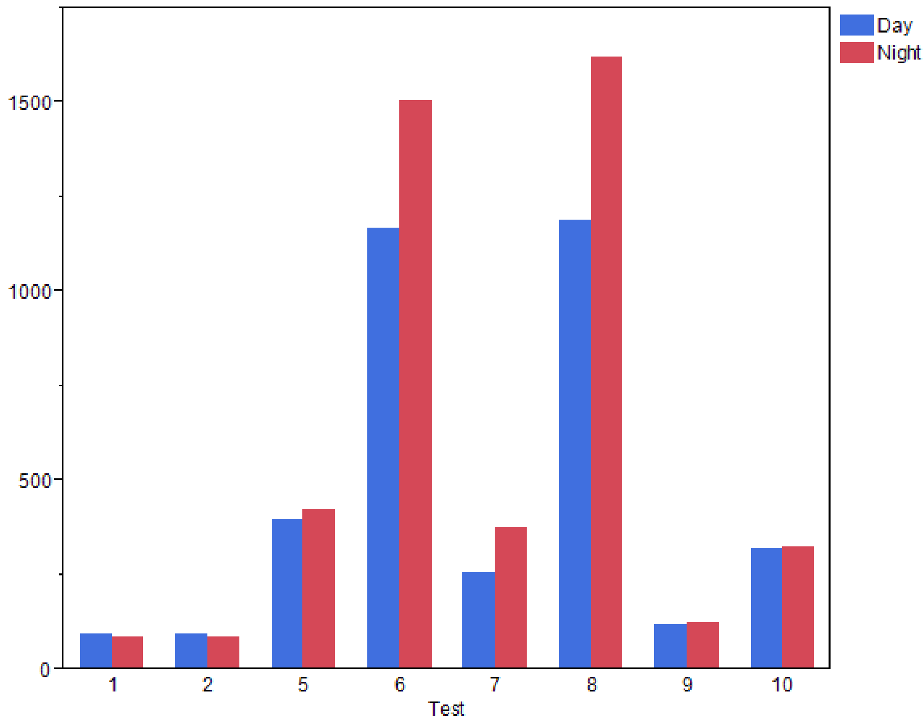

Figure 22: Hours of data collected for each test

Figure 23 shows the range of climatic conditions as recorded by the PWS for each test. The first three tests had higher temperatures as they were during the months of August through September. The remaining tests experienced relatively cooler temperatures. It is important to note that Test 1 does not share common temperatures with Tests 9 and 10; this makes direct comparison of the two tests impossible with respect to temperature. However, this problem will be addressed later in this chapter within the measure of performance. Florida is a humid climate, which is reflected by the average humidity ranging from 62.9-72.9%. The solar radiation ranged from 20 to 944 W/m^2 during Test; note that the Figure 23 only shows daylight hours (less than 20 W/m^2 was excluded as nighttime data). Overall, the mean wind speed was 4.8 miles per hour, and the direction varied but averaged 158º or south-southeast.

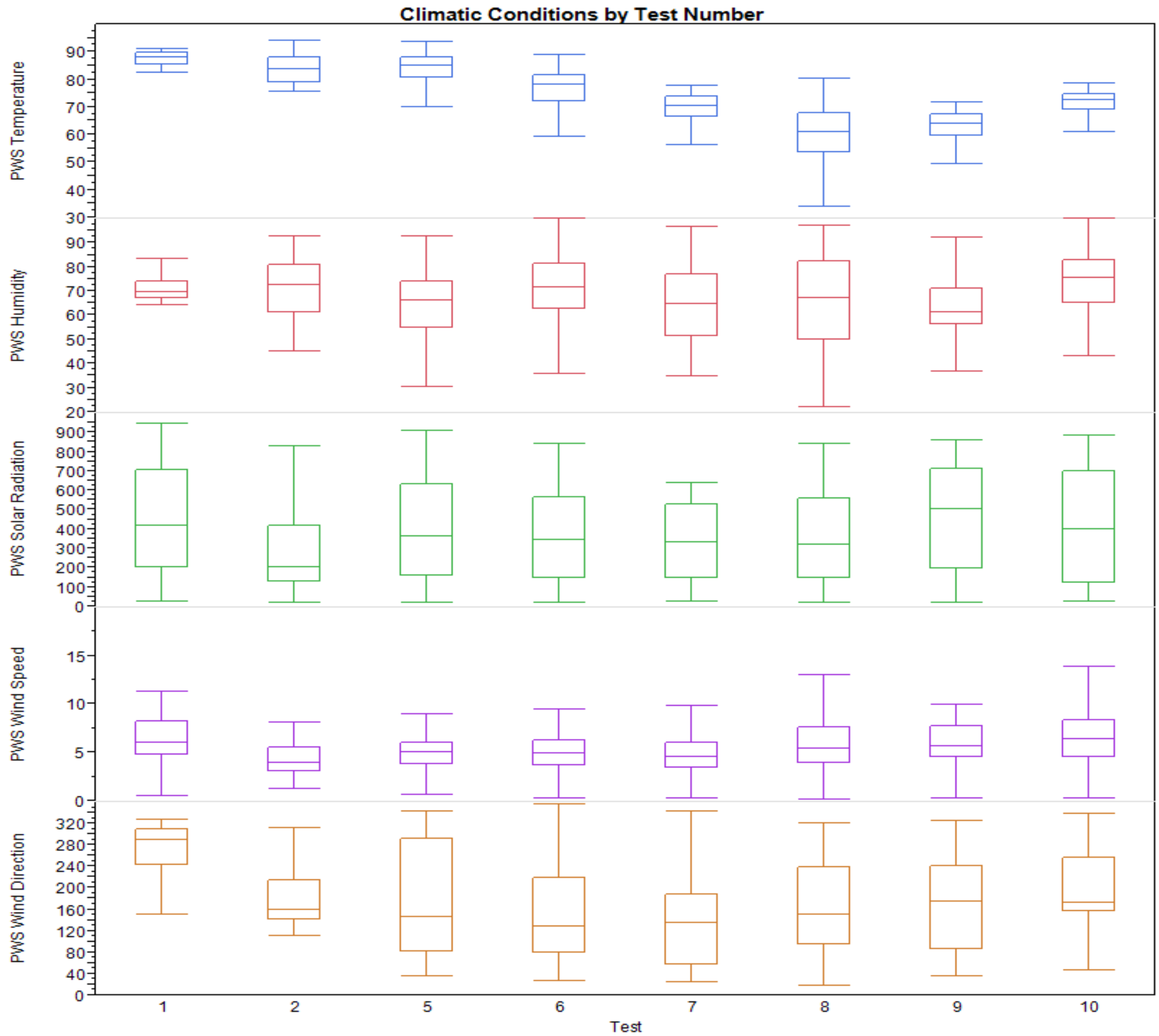

Figure 23: Range of climatic conditions as recorded by the PWS for each test

4.2.3 Measure of Performance.

Within a test, the jigs were exposed to identical climatic conditions, so the internal temperature can be used directly to quantify and compare the performance of the configurations and materials. However, the internal temperature alone cannot be used for comparing performance between tests. The range in climatic conditions per test must be considered when comparing the performance of the jigs from test to test. When the exterior conditions are not equal, the interior temperature of the jigs cannot be fairly compared as a measure of performance. To illustrate this point, Figure 24 shows the box plot of the jig's average interior temperature in red. From Figure 24, it could be concluded that the jigs in Test 8 performed the best as it had lowest interior temperature while the jigs in Test 1 performed the worst as they have the highest interior temperature. However, this does not account for the external temperature, shown in blue. In Test 1, the mean external temperature was 87.2 °F, 27.3 °F degrees higher than the mean temperature of Test 8. It is logical that the interior jig temperature of Test 1 would be higher than Test 8, as the exterior temperature is higher. Therefore, a direct comparison of interior temperature of the jigs is not a valid measure of performance between different tests.

To remove the bias created by the different external temperatures, the difference in temperature between the exterior and interior was used as the measure of performance. Figure 24 also shows in green the overall performance of the tests using the difference of temperature as the measure of performance. While Figure 24 still shows Test 1 as the poorest performing jig configuration, there is considerable difference in the relative performance of the remaining tests. In order to use this difference in temperature as a measure of performance, two assumptions must be made. First, the researcher assumes that the thermal performance of the jigs remains fairly constant over the range of the temperatures. This assumption introduces error as it is known that the R-value of insulation changes depending of the temperature at which it is measured. Second, the researcher assumes that the temperature is the primary climatic variable effecting the interior temperature. This assumption aligns with Medina's research and is validated in the next section [1].

Another concern highlighted by the figure is that the average temperatures inside the jigs are mostly higher than the outside temperature. The temperature is hotter inside because the interior space is not air conditioned or ventilated. In real world applications, this would not be true as there would be an Environmental Control Unit (ECU) cooling the interior space. However, the experiment is still valid as the jig's resistance to heat transfer works in both directions, meaning that the higher the resistance to heat transfer, the cooler the inside of the jig.

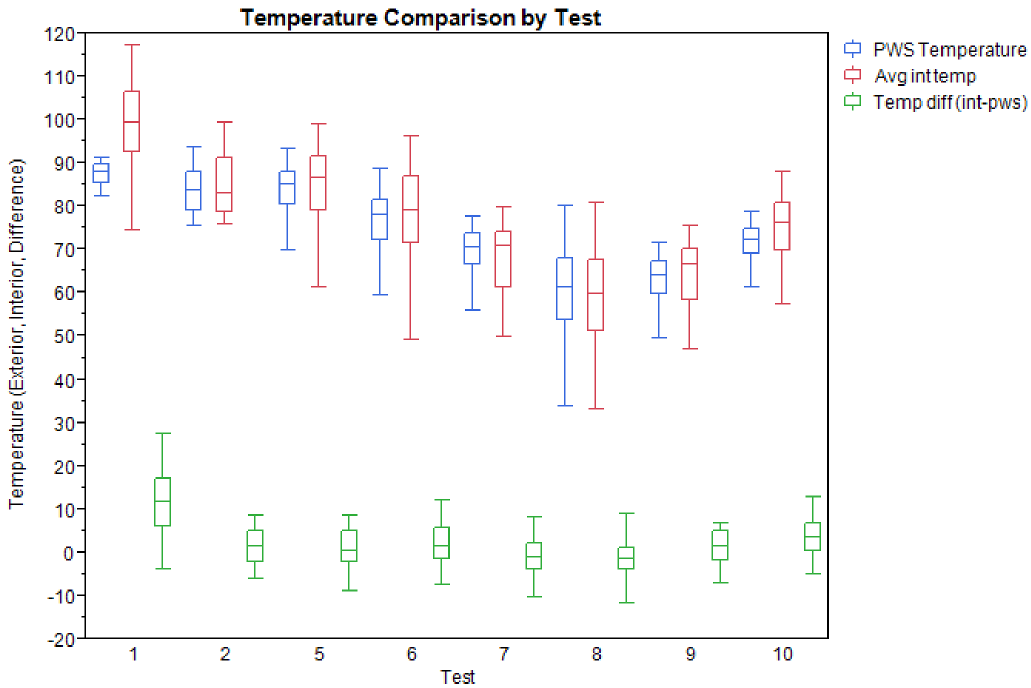

Figure 24: Variation in temperatures by test

4.2.4 Identification of Predictive Weather Variables.

The first research objective was to find the climatic variables with the greatest effect on the interior temperature of the shelters. To accomplish this, the data from the Portable Weather Station (PWS) was compared to the average interior temperature of the jigs. Correlations were calculated using JMP; results are shown in Table 8. The first analysis plots the exterior climatic variable against the interior temperature of the jigs.

Table 8: Correlation of jig interior temperature to climatic variables

Overall Average					
	Temperature	Humidity	Solar Radiation	Wind Speed	Wind Direction
Mean Correlation	0.883	-0.296	0.351	0.367	0.469
Standard Deviation	0.036	0.415	0.280	0.194	0.148

Table 8 shows a strong correlation between the exterior temperature and the interior temperature of the jigs, which is to be expected. However, the correlation between the interior temperature of the jig and the rest of the variables is relatively low, which is surprising. Because the standard deviation was higher for the other variables, each test and each jig was considered separately in Table 9.

Table 9: Individual correlation of jig interior temperature to climatic variables

Correlation of jig interior temperature to climatic variables						
Test	Jig	Temperature	Humidity	Solar Radiation	Wind Speed	Wind Direction
1	A	0.882	-0.829	0.829	0.398	0.330
2	A	0.806	-0.826	0.474	0.727	0.673
5	A	0.855	-0.428	0.273	0.385	0.541
6	A	0.917	-0.297	0.379	0.263	0.566
7	A	0.874	-0.034	0.008	0.099	0.503
8	A	0.928	0.467	-0.070	0.164	0.190
9	A	0.869	-0.266	0.288	0.528	0.534
10	A	0.920	-0.045	0.508	0.348	0.450
1	E	0.890	-0.845	0.868	0.453	0.275
2	E	0.823	-0.842	0.500	0.724	0.671
5	E	0.868	-0.451	0.299	0.388	0.522
6	E	0.913	-0.344	0.416	0.267	0.559
7	E	0.880	-0.076	0.042	0.098	0.494
8	E	0.929	0.457	-0.058	0.165	0.196
9	E	0.868	-0.279	0.303	0.522	0.539
10	E	0.906	-0.094	0.555	0.350	0.457

Similar to the correlation of average interior temperature and climatic variables for all tests combined, the individual analysis reveals a strong correlation between exterior temperature and the interior temperature of the jigs. However, these results are much more interesting as the effects of humidity, solar radiation, and wind speed and direction vary greatly between some of the tests. Two possible reasons for this variation are the degree of correlation between exterior temperature and the other climatic variables are different for each test or this may imply that the materials and/or configurations are causing a difference in the interior temperature of the jigs. The effects of the materials and configurations are considered in the following research objectives.

4.2.5 Effect of Number of Layers.

A multiple comparison of means using analysis of variance (ANOVA) was utilized to evaluate the effect of the number of layers in Table 10. Each test was categorized as having one, two, or three layers. All one-layer tests utilized skin only, two-layer test were either skin with liner or skin with fly, and three-layer tests utilized liner, skin, and fly. For two-layer tests, no consideration was given to the difference between the second layers, liner or fly, but this is analyzed later in section 4.2.9. To minimize the effect of differing external temperatures from test to test, the difference of temperature from the interior of the jig to the exterior temperature from the PWS was used as a measure of performance.

Table 10: ANOVA of the interior temperature by the number of layers

Number of Layers	Number of data points	Mean temperature difference (Jig interior temp - PWS temp)	Std Error	Lower 95%	Upper 95%
1	95	11.430	0.451	10.550	12.310
2	1584	2.347	0.110	2.130	2.560
3	1960	-0.798	0.099	-0.990	-0.600

The difference in mean temperatures were statistically significant for each group of the one-, two-, and three-layer configurations. This was expected as each layer provides some amount of thermal resistance and increasing the layers increases the total thermal resistance. The difference between one-layer and two- or three-layers is notable, suggesting that the addition of a second layer may create the greatest efficiency gain with diminishing returns as additional layers are added. However, this test had a low adjusted R-squared value of 0.218, suggesting that the number of layers alone is not a good predictor of the performance of the jigs. The increase in performance with additional layers aligns with the results from the hot box experiment.

4.2.6 Effect of Number of Radiant Barriers.

Similar to the test for the effect of number of layers, a multiple comparison of means using ANOVA was utilized to evaluate the effect of the number of radiant barriers (Appendix I contains both ANOVAs). Each test was categorized as having zero, one, two, or three radiant barriers. The breakout of possible combinations compared to what was actually tested can be seen in Table 11.

Table 11: Possible combinations of layer and radiant barriers with corresponding test

Possible test configuration with tests performed (Test-Jig)		Number of Radiant Barriers			
		0	1	2	3
Number of Layers	1	1-E	1-A		
	2	6-E	2-E 6-A 10-E	2-A 10-A	
	3	5-E	5-A 7-E	7-A 8-E 9-E	8-A 9-A

As shown in Table 11, for n layers there exists n+1 combinations because there could be no radiant barriers. This results in nine possible combinations of radiant barriers for the three layers, all nine of which were tested at least once. Again, no consideration was given to difference of a two-layer test having a fly or a liner and to minimize the effect of differing external temperatures from test to test, the difference of temperature from the interior of the jig to the exterior temperature from the PWS was used as the measure of performance.

Table 12: ANOVA of the mean temperature difference by number of radiant barriers

Number of Radiant Barriers	Number of data points	Mean temperature difference (Jig interior temp - PWS temp)	Std Error	Lower 95%	Upper 95%
0	831	2.950	0.162	2.631	3.268
1	1165	1.828	0.137	1.559	2.097
2	989	-0.286	0.149	-0.578	0.006
3	654	-1.620	0.183	-1.979	-1.261

The difference in mean temperatures were statistically significant for each group of the zero-, one-, two-, and three-radiant barrier configurations as shown in Table 12. The increase in the number of radiant barriers correlates to a decrease in relative interior temperatures, which aligns with the results from the hot box experiment. In this analysis, the difference between one- and two-radiant barrier configurations was most notable, suggesting that there are diminishing returns for additional radiant barriers after two. However, again the test had a low adjusted R-squared value of 0.111, suggesting that the number of radiant barriers alone is not a good predictor of the performance of the jigs.

Another analysis performed echoed the effect of increasing radiant barriers to the relative internal temperature of the jigs found in the previous test. This paired differences analysis compared Jigs A and E side-by-side for each test. Having the jigs compared side-by-side allowed for identical climatic conditions and the uses of the average internal jig temperature as the measure of performance. The hourly differences in temperature between Jigs E and A for each test is graphed as a box plot in Figure 25.

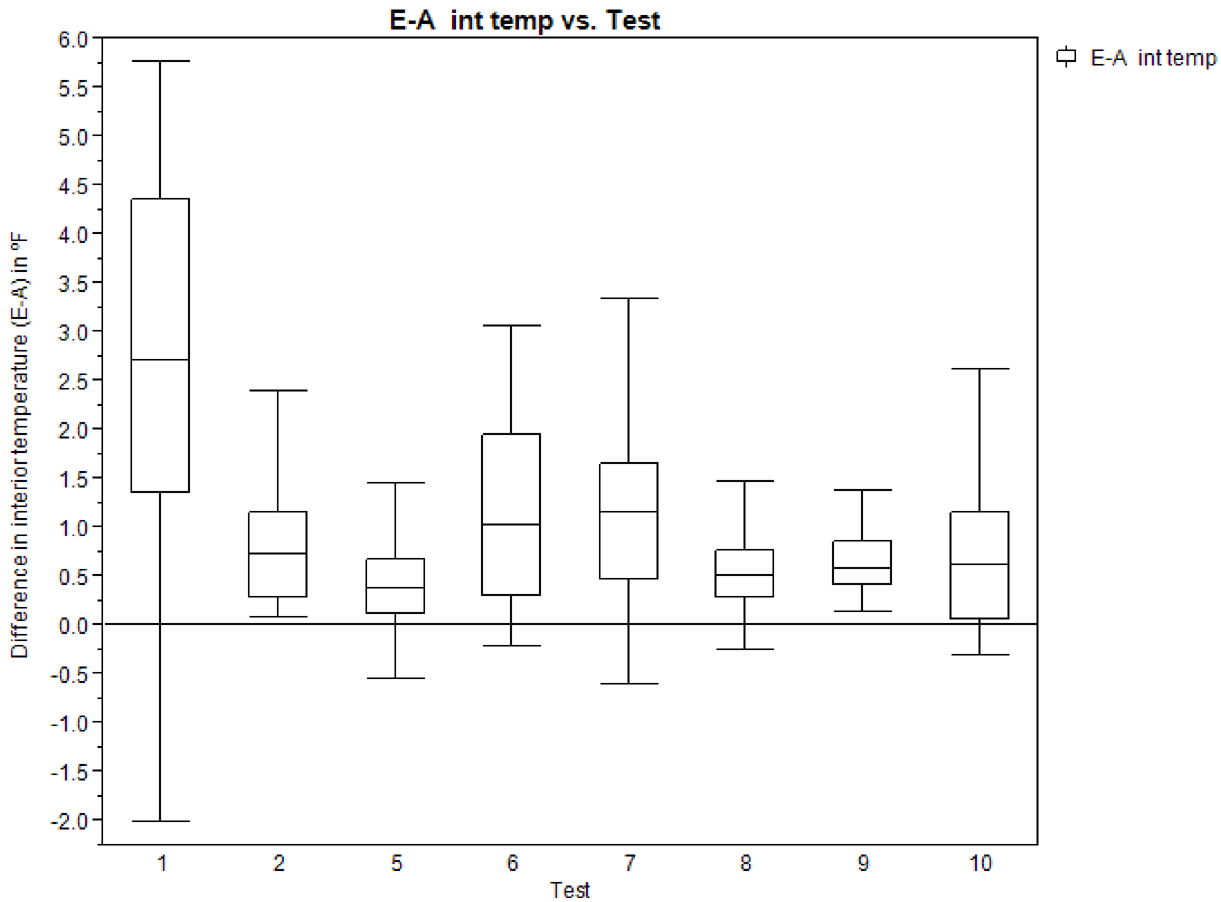

Figure 25: Difference in interior temperatures between Jig A & E

The graph in Figure 25 shows the average interior temperature of jigs without a radiant barrier (Jig E) is always hotter than average temperature of jigs with a radiant barrier (Jig A) as the mean of each test is greater than zero. This suggests that the addition of one radiant barrier always increases performance, at least up to three radiant barriers. It also show the greatest temperature difference occurred in Test 1, which is the only test with one layer. This is consistent with the results from the hot box experiment without A/C which suggested that a single layer system should utilize a radiant barrier.

4.2.7 Interaction of Number of Layers and Number of Radiant Barriers.

Increasing the number of layers and the number of radiant barriers both appear to have a positive effect on the performance of the jigs. Therefore, the interaction of the two variables were analyzed. Table 13 shows the two-way ANOVA comparing the effect of each variable to the resulting difference in temperature. This table show that the number of layers is the main effect. Figure 26 depicts the difference in temperature for one-layer (red), two-layer (green), and three-layer (blue) depending on the number of radiant barriers. None of the lines cross, indicating that there is no significant interaction between the number of layers and number of radiant barriers. This confirms that both the number of layers and number of radiant barriers contribute individually to the thermal performance of the jigs.

Table 13: Two-way analysis of number of layers and radiant barriers

Possible test configuration		Number of Radiant Barriers				Average Difference in Temp (°F)
		0	1	2	3	
Number of Layers	1	12.72	10.11			11.42
	2	2.75	1.95	2.71		2.47
	3	1.17	0.33	-1.08	-1.62	-0.30
Average Difference in Temp (°F)		5.55	4.13	0.82	-1.62	

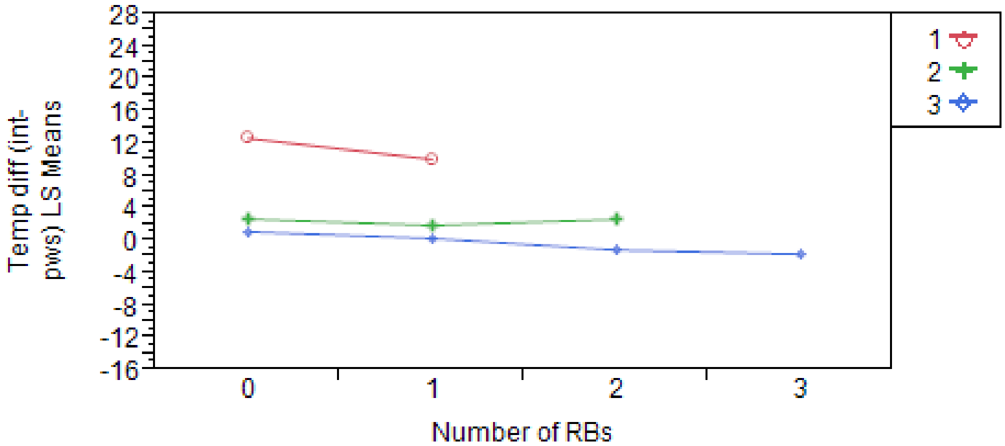

Figure 26: Interaction of number of layers and radiant barriers

4.2.8 Effect of Direction of Radiant Barrier Liner.

A comparison of means using analysis of variance (ANOVA) was utilized to evaluate the effect of the direction of the radiant barrier liner. Test 8 and Test 9 were configured the same with three layers, except the liner was reversed, or facing inwards for Test 9. Again, to minimize the effect of differing external temperatures from test to test, the difference of temperature from the interior of the jig to the exterior temperature from the PWS was used as the measure of performance.

Table 14: Performance comparison of radiant barrier facing outward versus inward

Test Number	Number of data points	Mean temperature difference (Jig interior temp - PWS temp)	Std Error	Lower 95%	Upper 95%
8 (outward)	1190	-1.5701	0.1158	-1.797	-1.343
9 (inward)	118	1.0803	0.3678	0.359	1.802

Table 14, shows the mean temperature was significantly different between Test 8 and Test 9. The lower mean temperature in Test 8 suggests that the radiant barrier liner should be faced with the radiant barrier towards the outside to be most effective. This suggestion aligns with the results from the hot box test.

4.2.9 Effect of Second Layer as a Fly or Liner.

A comparison of means using ANOVA was utilized to evaluate the effect of the second layer of a two-layer configuration to determine if a fly or liner is more effective. Tests 2, 6, and 10 were used for the analysis as they each had exactly two layers; Test 2 and 6 utilized liners while Test 10 utilized a fly. To minimize the effect of differing external temperatures from test to test, the difference of temperature from the interior of the jig to the exterior temperature from the PWS was used as the measure of performance.

Table 15: Performance comparison between second layer as a fly or liner

	Number of data points	Mean temperature difference (Jig interior temp - PWS temp)	Std Error	Lower 95%	Upper 95%
Liner	1264	2.016	0.122	1.776	2.256
Fly	320	3.653	0.243	3.177	4.129

Table 15 shows the mean temperature was significantly different between tests with a liner as compared to tests with a fly. The lower mean temperature in tests with a liner suggests that the liner is a more effective second layer than the fly if only two layers can be used.

4.2.10 Modeling of Jig Performance.

The previous sections of this chapter made use of the difference of temperature from the inside of the jig to the outside of the jig as a measure of performance to compare the effectiveness of the number of layers, radiant barriers, radiant barrier direction, and the use of a fly or liner between different tests. In this section, a model was created for each Jig A test allowing for direct comparison of internal jig temperature as a measure of performance. The models were created using JMP®. First, a stepwise regression was performed using the climatic conditions as the independent variables and the average interior temperature of the jig as the response, or dependent variable. A P-value threshold of 0.25 was set and the predictive variables were identified. These variables were used to create the model for each test and jig individually. The model creation and corresponding assumption tests are provided in Appendix J.

While using the jig's internal temperature as a measure of performance eliminates assumptions and possible errors introduced by using the temperature difference, it also introduces its own set of challenges. Most notably, as established in the summary statistics, not all tests share a common range of values for the climatic conditions. Therefore, to compare models at equivalent conditions, some models must predict performance outside of the range in which they were built. The original intent of modeling each jig was to compare all the jigs at conditions they would be subjected to while deployed in the Middle East, namely 1120 W/m^2 and 120°F with low humidity; however, these conditions are considerably outside of the actual built range of the models. Therefore, the average environmental condition experienced during each testing period was used to compare the models, specifically 66.6% for humidity, 442.8 W/m^2 for solar radiation, and a wind speed of 5.87 mph at 187.1° from North. These models were graphed in Figure 27 holding these averages constant while varying the exterior temperature.

The graph of the models in Figure 27 shows, with few exceptions, the performances are tightly clustered with similar slopes. Figure 28 offers a closer look at Figure 27, allowing for a clearer picture of the separation between the tests with a dashed line representing the continuation of the slope outside of the built range. The models along with their configurations are listed in order of performance in Table 16, with the highest performing at the top. In cases where the models cross, the researcher's judgment is used to order the models with consideration given to the performance of the jigs at temperatures higher than 81°F and models that are within the built range.

The two top performing models both utilized radiant barrier liners facing outwards with radiant barrier skins. The top performing configuration included three layers, all of which were radiant barriers. The second best configuration only utilized two layers, both of which were radiant barriers. The tests without liners performed the worst, with the standard and reversed liners filling out the middle. No conclusions can be made about fly as there is no discernable pattern. The models suggest that Test 8 is the best three-layer configuration while Test 2 is the best two-layer configuration.

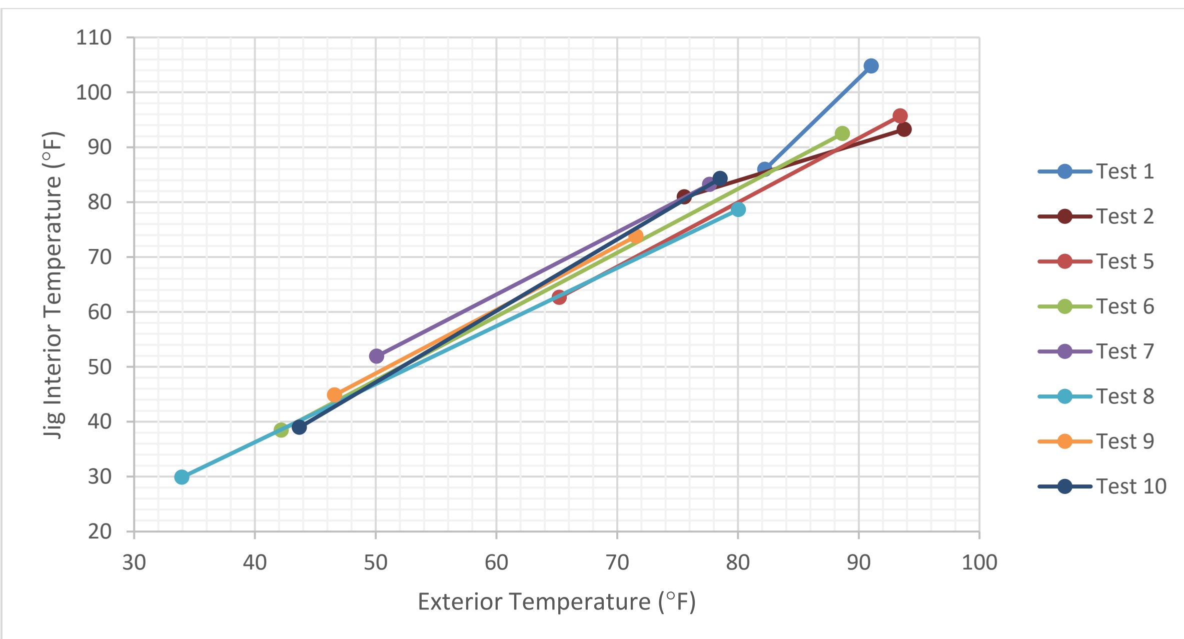

Figure 27: Graph of Jig A performance models over built range

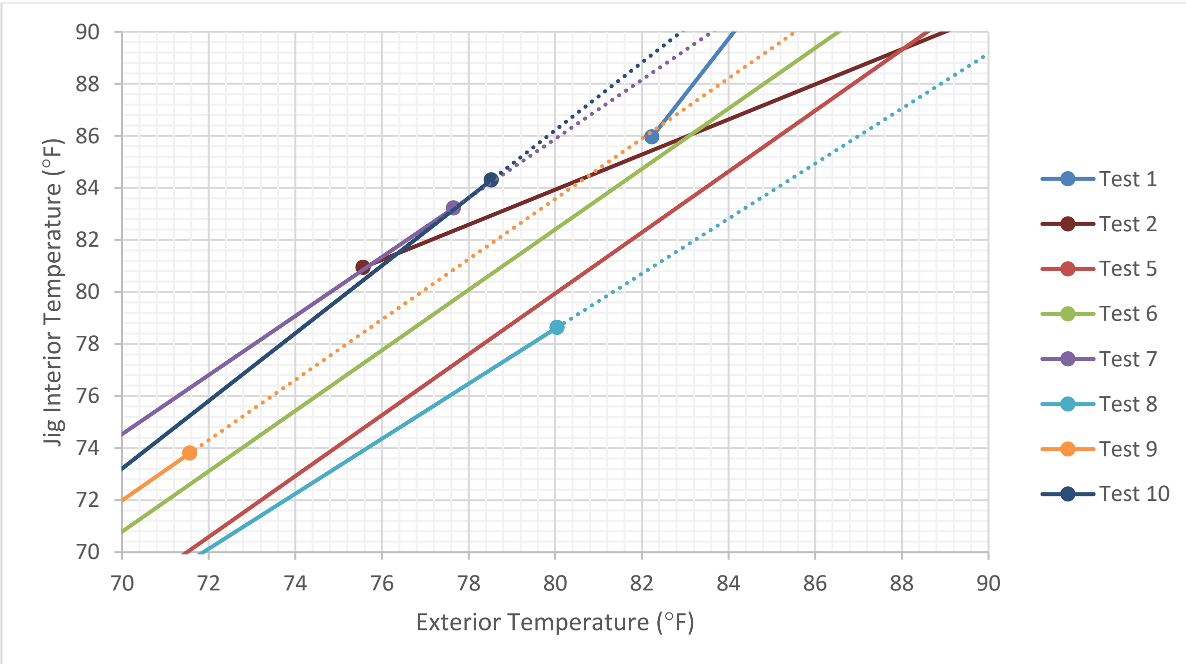

Figure 28: A closer look at Jig A performance models with trend lines added

Table 16: Test configurations ordered by increasing model performance

		Liner			Skin	Fly	
	Test	RB	Std	RB Reversed	RB	Std	RB with Mesh
Best	8	X			X		X
	2	X			X		
	5		X		X	X	
	6		X		X		
	9			X	X		X
	7		X		X		X
	10				X		X
Worst	1				X		

4.1.11 Limitations.

The test jigs are an economical alternative to full-scale test for evaluating the thermal performance of fabric materials. However, the overall size, shape, fabric angles, and distances in between layers are generic as they are not built to the specifications of a specific shelter type. While the set-up of the test jigs are generic, the data is still useful as the testing methods were consistent. Therefore, the test configurations can be compared against each other. Also, similar to the hot box apparatus, the small-scale of the material may experience less air movement within the air space due to convection currents, possibly resulting in more favorable results. Finally, the test jigs experiment was located at Tyndall AFB, Florida, which experiences cooler temperatures and higher humidity than the hot, dry characterization of the Middle East. To minimize potential error introduced by the different climate, future test should be performed in climates more similar to that of the Middle East.

4.1.12 Test Jig Summary.

The data collected from the test jig experiments indicate that the number of layers and number of radiant barriers is positively correlated to the thermal performance of the temporary fabric shelters. Next, the liner outperforms the fly if only two layers are used, and the radiant barrier liner should be faced outwards. The multiple regression model developed for the thermal performance of the test jigs identifies the best performing three-layer system as Test 8 with three radiant barrier layers, the fly being mesh. Also, the model identifies the best two-layer system as Test 2 with a radiant barrier liner and skin. The model confirms the previous finding of both the hot box and test jigs, suggesting internal validity of the experiments and model. While the design of the test jigs is generic with respect to a specific shelter, the data is still useful as the testing methods were consistent.

4.3 Full-Scale Experiment

AFCEC performed a series of full-scale tests throughout the world and provided data on the climatic conditions inside and outside of the temporary fabric structures. However, these full-scale tests introduce a host of additional variables, making it increasingly difficult to isolate the effects of the materials and configurations, thus creating uncertainty. The main source of uncertainty comes from the construction of the shelters. In an idealized scenario, each shelter would be built and constructed in the exact same way; however, this is not the case. In the field, the shelters experience infiltration of air through gaps in the layers, separated seems, and small holes in the fabric. Depending on how the layers are stretched and secured, the air gaps between the layers will vary and will not be uniform. Furthermore, the shelters are connected together in close proximity, causing shelters to shade each other and block the wind, so shelters sitting side-by-side still do not experience the same climatic conditions. While all of these variations have to be considered in the final design of next-generation temporary fabric shelters, they are beyond the scope of this research. Once the optimal materials and configurations are identified using small-scale tests in the controlled environment of a hot box or the more simplistic test jig, then full-scale tests should be conducted. For these reasons, the full-scale data was not analyzed in this research but presents an opportunity for further research.

V. Conclusion

5.1 Research Objectives

The purpose of this research was to aid the Air Force Civil Engineer Center (AFCEC) in the design, testing, and procurement of next-generation temporary fabric shelters. Specifically, this research focused on the thermal performance of different types and configurations of fabric materials used for the fly, skin, and liner of the shelters. Climatic variables effecting thermal performance of fabric shelters were identified along with characteristics of the environment in which the shelters are expected to perform. Then, testing procedures and thermal performance metrics were analyzed and established. Finally, different material and configuration were tested.

The specific objectives of this research were to:

1. Determine how to measure thermal performance of fabric structure materials.
2. Determine the most thermally efficient material composition of fly, skin, and liner.
3. Determine the most thermally efficient configuration of fly, skin, and liner.
4. Determine if the same technology can be applied to medium and large shelters.

Because the military and industry do not have a specific regulation for testing temporary fabric shelters, it was necessary to establish a test method and performance metric. Then, by identifying the most influential weather variables, AFCEC can simplify future tests, focusing primarily on the most important variables. Finally, by knowing the optimal number of layers, number of radiant barriers, and placement and direction of radiant barriers, AFCEC can establish a minimum thermal performance to include in contract specifications as a baseline for future shelters and the method that will be used to evaluate performance.

5.2 Research Results

5.2.1 Objective 1: Determine how to measure thermal performance of fabric structure materials.

The controlled environment of the hot box apparatus is the preferred test method over the test jigs for comparison of thermal performance of materials. However, the performance metric can be changed to make either test method useful for the comparison of different configurations.

Two methods were utilized in this research to test the thermal performance of the materials used in temporary fabric shelters, the modified hot box apparatus and test jigs. The hot box apparatus method is preferred as it provides a controlled environment, allowing similar conditions for each test. However, because the hot box apparatus used in this research was not professionally manufactured and calibrated, error was introduced as discussed in limitation, Section 4.1.11. Test jigs are also a valid method for testing the thermal performance of the materials used in temporary fabric shelters. The advantage of the test jigs are that the materials are exposed to real world conditions. However, the disadvantage is that configurations must be tested at the same time, side-by-side, otherwise statistics heavy modeling is required to compare results. Also, the test jigs must be tested under conditions similar to the environment in which they will be expected to perform as modeling outside of the built range significantly decreases the confidence of the model. Along with determining the method of measuring thermal performance, the metric of thermal performance was also established.

Determining the metric for thermal performance was accomplished through a combination of literature review and gaining understanding of AFCEC's needs. The researcher determined A/C runtime could be used for the hot box apparatus to compare different tests. For the test jigs, interior temperature was used to compare jigs tested at the same time, while difference in temperature was used to compare jigs tested at different times. However, climatic conditions for the test jig should be representative of the environment in which they must perform, in this case the climate of the Middle East.

The researcher characterized the environmental conditions of the Middle East in a journal article [35]. While environmental conditions vary throughout the Middle East the overall the region is classified as hot and dry with Kuwait representing the most extreme conditions in the area [32, 35]. The standard for solar radiation of 1120 W/m^2 and ambient temperature of 120°F is used to represent "the hottest conditions exceeded not more than one percent of the hours in the most extreme month at the most severe locations" [31]. These standards were not achieved in either the hot box or test jigs, so the performance of the materials in these extreme conditions can only be cautiously interpolated from the less extreme test conditions.

The hot box apparatus only controlled and recorded the climatic variables of temperature and solar radiation, so performance was correlated to those two variables. In addition, temperature and solar radiation, the test jig data included humidity, wind speed and direction, allowing correlations to be drawn between performance and all five variables to determine which variable are most influential. The correlation between the exterior temperature and the interior temperature for all configurations was high, with little variance. The effect of the exterior temperature was confirmed by the performance models created for each jig in which the exterior temperature had the greatest overall effect. Surprisingly, humidity did not have a strong correlation with the overall performance and had a high variance between different tests. The remaining variables of solar radiation, wind speed, and wind direction also did not have a significant effect of the performance. With the exception of humidity, these results are consistent with the literature review, specifically Medina's tests on attic radiant barriers [1].

5.2.2 Objective 2 & 3: Determine most thermally efficient material composition and configuration of fly, skin, and liner.

Objectives 2 and 3 were accomplished by a design of experiments with tests conducted in both the hot box apparatus and the test jigs. Specifically the following effects were tested.

1. Identify the effect of the number of layers
2. Identify the effect of the number of radiant barriers
3. Identify the effect of the direction of radiant barriers
4. Identify if the fly or liner is more effective
5. Identify the best jig configuration

5.2.2.1 Effect of the number of layers.

Both the hot box and test jig experiments confirmed that increasing the number of layers increases the performance. This is logical as each layer of material and the air gap in between provides thermal insulation.

For the hot box experiments, the number of layers appeared to be the primary factor determining the success of the tests. Every experiment with only one-layer failed, five of the seven two-layer experiments passed, and every three-layer experiment passed. Additionally, when the A/C runtime was compared to the number of layers, the trend line showed a decrease in runtime with an increase of layers. However, the relatively low adjusted R-squared value of 0.53 from the ANOVA suggested that the number of layers is not the only variable effecting thermal performance.

For the test jig experiments, the difference in mean temperatures were statistically significantly for each group of the one-, two-, and three-layer configurations. The difference between one-layer and two- or three-layers is notable, suggesting that the addition of a second layer may create the greatest efficiency gain with diminishing returns as additional layers are added. However, this test had a low adjusted R-squared value of 0.13, suggesting that the number of layers alone is not a good predictor of the performance of the jigs.

5.2.2.2 Effect of the number of radiant barriers.

Both the hot box and test jig experiments suggest that increasing the number of radiant barriers increases thermal performance.

For the hot box experiments, increasing the number of radiant barriers appears to be correlated with increased performance, but the results are not conclusive. Every experiment with two or more radiant barriers passed. Additionally, when the A/C runtime was compared to the number of radiant barriers, the trend line showed a decrease in runtime with an increase of radiant barriers, except in the case of three radiant barrier in which only one test was conducted. However, while the trend line suggests a correlation, the Tukey analysis showed no significant difference between the groups and the ANOVA with a low adjusted R-squared value of 0.23 suggested that the number of radiant barriers is not strong predictor of thermal performance.

For the test jig experiments, the difference in mean temperatures were statistically significant for each group of the zero-, one-, and two-radiant barrier configurations. The increase in the number of radiant barriers correlates to a decrease in relative interior temperatures. In this analysis, the difference between one- and two- radiant barrier configurations was most notable, suggesting that there are diminishing returns for additional radiant barriers after two. However, again the test had a low adjusted R-squared value of 0.111, suggesting that the number of radiant barriers alone is not a good predictor of the performance of the jigs. Additionally, the side-by-side comparison of Jig A and E for each test showed an increased performance with the additional radiant barrier suggesting that the addition of radiant barrier always increases performance, at least up to three radiant barriers.

5.2.2.3 Effect of the direction of radiant barriers.

Both the hot box and test jig experiments confirmed that the radiant barrier should be faced outwards to increases the performance. This is logical as the radiant barrier was designed to face towards the source of solar radiation and the liner contains a batt insulation material, which is exposed to the radiation when outside of the radiant barrier.

For the hot box experiments, the effects of the direction of a radiant barrier liner was observed in Test 8 and Test 11. The A/C runtime of Test 8 with the radiant barrier facing outward was 13.6% shorter over the two-hour test. While a conclusion cannot be made from two data points, the results suggest that facing the radiant barrier outward is more effective. For the test jig experiments, the mean temperature was significantly different between Test 8 and Test 9. The lower mean temperature in Test 8 suggests that the radiant barrier liner should be faced with the radiant barrier towards the outside to be most effective.

5.2.2.4 Effectiveness of fly versus liner.

The liner is a more effective second layer than the fly.

Only the test jig experiment was used to evaluate the effectiveness of the fly versus the liner as all hot box experiments with two layers only utilized the skin and liner combination. Tests 2, 6, and 10 were used for the analysis as they each had exactly two layers; Test 2 and 6 utilized liners while Test 10 utilized a fly. The mean temperature was significantly different between tests with a liner as compared to tests with a fly. The lower mean temperature in tests with a liner suggests that the liner is a more effective second layer than the fly if only two layers can be used.

5.2.2.5 Identify the best two-layer and three-layer configurations.

The best performing configuration utilized three layers consisting of a radiant barrier liner and skin with a mesh fly. The best performing two-layer configuration utilized a radiant barrier liner with a radiant barrier skin.

For the hot box experiment, Test 4 was by far the best performing configuration of the 16 tested. The configuration consisted of three layers with radiant barrier skin and liner and a mesh fly. The A/C ran for 0.89 hours consuming 0.663 kWh, which was 26.1% more efficient than the next best test. Test 8 was the best performing two-layer test. The configuration consisted of both radiant barrier skin and liner. The A/C ran for 1.37 hours consuming 1.05 kWh, which is 36.9% less efficient than the best three-layer test. For the test jigs, according to the model, the best performing configuration utilized all three layers, each a radiant barrier. The best performing two-layer configuration utilized a radiant barrier liner with a radiant barrier skin. Both tests agree that the best system will utilize a radiant barrier liner and skin, and if a third layer is allowed, it should be a mesh fly. In all, the best configurations align with all the previous observations that increased number of layers, increased number number of radiant barriers, and facing radiant barriers outward results in the best performance.

5.2.4 Objective 4: Determine if the same technology can be applied to medium and large shelters.

Due to the physical limitations of shelter construction in the field, only two layers should be used for medium and large shelters. This required the identification of the best two-layer system. Both the hot box and test jig results agree that the best system will utilize a radiant barrier liner and skin with radiant barriers facing outwards. The batt insulation integrated into the radiant barrier liner has been proven more effective than a radiant barrier fly as a second layer. This could be advantageous to AFCEC as existing structures could be retrofitted with radiant barrier liners and used in conjunction with adjustable attic spaces if the concept is proven to be effective.

5.3 Limitations

In addition to the limitations in Chapter 4 specific to each test, overall limitation for the research conclusion must be considered. The initial intent of this research aimed to determine the best shelter material and configurations for use in the Middle East. However, both the hot box apperatus and test jigs failed to simulate the intense climatic conditions characterization specified for the Middle East. While the results are still usefull when interpreted within the climatic parameters of the actual test, caution is require when extraploting this data past the tested range. Hence, the hot box conclusion are most applicable for conditions around 110°F with solar radiation of 480 W/m^2. While the test jigs conclusion are most applicable for climatic conditions similar to the conditions in Tyndall Air Force Base (AFB), Florida.

Finally, the metric used to capture the thermal performance of the fabric materials is not the same as the R-value used in traditional building materials or the heat flux used in testing radiant barrier performance in attics [10, 14]. While the shelters are non-typical construction types, it may be useful to be able to compare the thermal performance of the fabric shelters to other types of portable shelters in the future.

5.4 Research Significance

The significance of this researcher extends far beyond the identification of the best composition and configuration of material. Knowing an achievable thermal resistance of temporary fabric shelters will aid the Air Force and Army's group project to develop and demonstrate deployable Advanced Energy Efficient Shelter Systems with the short term goal to be 50% more energy efficient than the current generation of shelters and ultimate goal of net-zero energy. Reducing the cooling load required for the inherently inefficient temporary fabric shelters, which makes up an estimated 60% of the overall base operating support electrical load, will results in a massive point-of-use power savings in the deployed environment [4, 9]. The amount of fuel required to power Environmental Control Units (ECUs) can be reduced, along with the number of ECUs. This equates to fuel cost savings and decreases the amount of fuel convoys, mitigating the risk to troops assigned to deliver the fuel to austere locations [7]. Additionally, reducing dependency on fuel allows for increased range and force maneuverability, ultimantley reducing risk to the mission [3].

5.5 Future Research and Recommendations

This research is just one piece of the much larger project, Advanced Energy Efficient Shelter Systems. There are many research opportunities that could support this project to include integrating solar panels into the shelter material, use of hard-scaped doors, adjustable attic spaces to reduce the volume of air needed to be conditioned, energy efficient lighting, and insulated flooring. For additional information on Advanced Energy Efficient Shelter Systems and related research opportunites, interested parties can contact the AFCEC Energy Directorate for Expeditionary Energy.

There is also oportunity for future research directly related to the thermal performance of temporary fabric shelter materials. To increase the reliability of the hot box results, a full design of experiments (DOE) using materials from only one manufacturer should be conducted using a manufactured hot box from a reputable testing equipment manufacturer. The full-spectrum lamps used as the heat source should conform to Military Standard 810G for spectrum distribution and coverage to ensure the entire surface area of the material is exposed to equal amounts of radiation [31]. Surface temperature sensors with exposed thermistors should be secured to surfaces and covered with a patch of the same material to prevent direct exposure to the full-spectrum lamp. Thermocouple probes should be added to capture the temperature of the air gaps between layers. Tests should be conducted in 24-hour cycles with temperature and solar radiation intensities changing to mimic the hourly conditions of the climate in which the shelter is expected to perform [31].

Further research on the test jigs should also include a full DOE using materials from only one manufacturer. The primary limitation of the test jigs was the location in which they were tested. Tyndall AFB, Florida experiences cooler temperatures and higher humidity than the hot, dry characterization of the Middle East. To minimize potential error introduced by the different climate, future test should be performed in climates more similar to that of the Middle East. The test could also be expanded to capture climates other than the Middle East. Ongoing photovoltaic energy research has identified bases representative of every climatic region in which Air Force real property is located [36]. Coupling the test jig locations with these identified bases would provide a global picture of material performance.

Finally, if the same DOE is tested in the hot box and test jigs, the difference in performance between a controlled environment verses a real world environment could be quantified. Future research could also utilize the full-scale data to model the heat transfer occurring in the temporary fabric shelters. With a full-scale model, different size, shapes, and orientations of shelters could be tested along with AFCEC's concept of an adjustable attic space. Additionally, emerging thermal products such as aerogel fabrics could be explored as another type of isolative material. Lastly, a behavioral study of the shelter occupants could be used to improve shelter design as troops down range customize and alter the shelters to meet their needs.

Appendix A. Additional information on hot box equipment and sensors

Home / Products / Global Industrial SAC-18 Portable Air Conditioner - Spot Cooler - 6,200 BTU,

Global Industrial SAC-18 Portable Air Conditioner - Spot Cooler - 6,200 BTU,

BRAND: Global Industrial

WIDTH INCHES: 18-11/16

DEPTH INCHES: 10-3/8

HEIGHT INCHES: 24

WEIGHT LBS: 51

ASSEMBLY: Assembled

CONSTRUCTION: Steel / Plastic

BTU COOLING: 6,200

REFRIGERANT: R407-C

COOLING SQUARE FEET: 250

VOLTAGE: 115

HERTZ (HZ): 60

WATTS: 650

DEHUMIDIFICATION PINTS / HOUR: 0.6

POWER CORD LENGTH FEET: 5

DECIBELS (DBA): 50

APPROVAL: ETL & CSA C22.2 No.117

LIMITED WARRANTY YEARS: 1

APPLICATION: Commercial

Buy This Product $ 149

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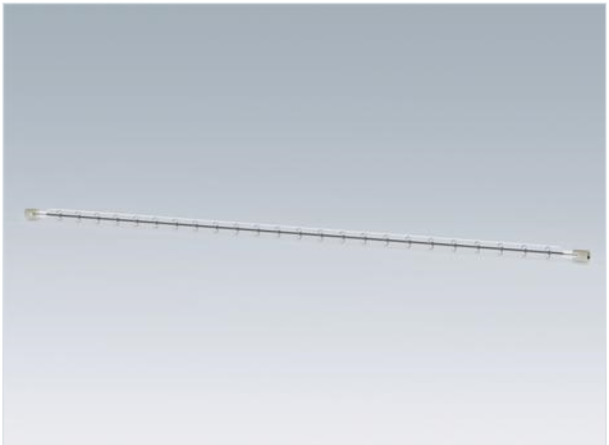

Quartz Halogen Long Wave Heater

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VOLTAGE SELECT YOUR VOLTAGE...

INQUIRE ADD TO WISHLIST +

DETAILS

Available in standard 240 voltage and non standard 480 voltage
Dimensions: 10 x 473mm
For other options, please contact us directly.

Quartz Halogen Long Wave Heaters are filled with halogen gas. This is to allow the supported tungsten filament to reach temperatures of 2600°C (4712°F).

Peak wavelength emissions are 1 micron, allowing rapid on/off cycles.

http://www.wecointernational.com/shop/quartz-halogen-long-wave-heater/

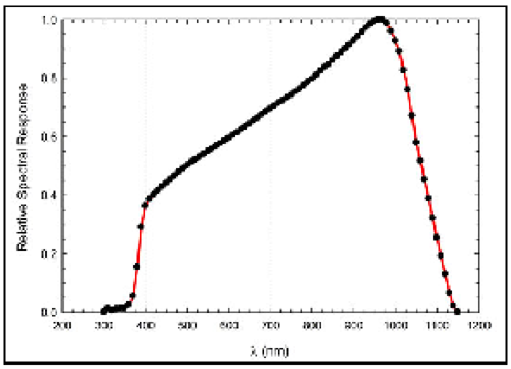
Pyranometer

(PYR-BTA)

The Vernier Pyranometer measures the power of electromagnetic radiation in watts per square meter. It is sensitive to the near infrared, visible, and UV ranges, where nearly all of the solar energy is concentrated. It is great for experiments with solar cells and calculating their efficiency. The sensor is weatherproof and has a dome-shape top to allow it to work with a wide range of sun angles. The Pyranometer has a 6 m cable.

An ideal pyranometer measures the entire solar spectrum, 280 to 2800 nm. However, about ninety percent of sunlight energy is in the wavelengths between 300 and 1100 nm. The Vernier Pyranometer detects all of this energy.

The Vernier Pyranometer is cosine corrected and is designed to maintain its accuracy when radiation comes from different angles. The cosine response when the sun is at 75° to the zenith is ± 5 percent. Zenith angles greater than 75° contribute less than 3 percent of daily radiation.



Spectral response of the Vernier Pyranometer

What is Included with the Pyranometer

- Pyranometer
- Cover for the lens of the Pyranometer

Mounting the Pyranometer

The Pyranometer is designed to be permanently mounted outside. It is weatherproof and has a lens to work with a wide range of sun angles. The sensor, itself, is designed for continuous outdoor use. The black electronics box should be kept dry.

The Pyranometer should be mounted with the white lens pointing straight up and with the cord pointing toward the north (if you are in the Northern Hemisphere) or toward the south (if in the Southern Hemisphere).

The nylon 10–32″ x 3/8″ mounting screw can be used for attaching the Pyranometer to a solid object.

Cleaning the Pyranometer

Debris on the Pyranometer lens is a common cause of low readings. Salt deposits can accumulate on the sensor from evaporation of sprinkler irrigation water, and dust can accumulate during periods of low rainfall. Salt deposits should be dissolved and removed with vinegar and a soft cloth or cotton swab. Dust and other organic deposits are best removed with water, rubbing alcohol, or window cleaner. Never use an abrasive cleaner on the lens.

Collecting Data with the Pyranometer

This sensor can be used with the following interfaces to collect data.

- Vernier LabQuest® 2 or original LabQuest as a standalone device or with a computer
- Vernier LabQuest Mini with a computer
- Vernier LabPro® with a computer or TI graphing calculator
- Vernier Go!®Link
- Vernier SensorDAQ®
- Vernier EasyLink®
- CBL 2™
- TI-Nspire™ Lab Cradle

Data-Collection Software

This sensor can be used with an interface and the following data-collection software.

- **Logger *Pro* 3** This computer program is used with LabQuest 2, LabQuest, LabQuest Mini, LabPro, or Go! Link.
- **Logger Lite** This computer program is used with LabQuest 2, LabQuest, LabQuest Mini, LabPro, or Go! Link.
- **LabQuest App** This program is used when LabQuest 2 or LabQuest is used as a standalone device.
- **LabVIEW™** National Instruments LabVIEW™ software is a graphical programming language sold by National Instruments. It is used with SensorDAQ and can be used with a number of other Vernier interfaces. See www.vernier.com/labview for more information.
- **DataQuest™ Software for TI-Nspire™** This calculator application for the TI-Nspire™ can be used with the EasyLink or TI-Nspire™ Lab Cradle.

Go!Temp®

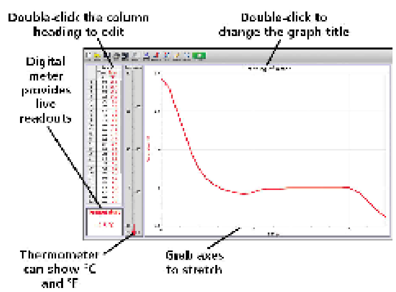
(GO-TEMP)

Go!Temp is a USB temperature probe that can be used to collect data when connected to a computer, LabQuest®, or Chromebook™.

Getting Started

Go!Temp with a Computer

1. Install Logger Lite® (or Logger *Pro*®) software on your computer.
   - Logger Lite is free and can be downloaded at www.vernier.com/loggerlite
   - Logger *Pro* has many additional features and is available for purchase at www.vernier.com/lp
2. Connect Go!Temp to the computer's USB port.
3. Start the software. Go!Temp will be recognized and will display the live temperature reading.
4. Click Collect to begin collecting temperature data or open an experiment file from one of the Vernier lab books.



Go!Temp with a LabQuest

1. Connect Go!Temp to the USB port on the LabQuest 2 or original LabQuest.
2. Go!Temp will be recognized and will display the live temperature reading.
3. Start data collection, if desired.

Go!Temp with a Chromebook

1. Install Graphical Analysis™ (version 1.2 or newer, available in the Chrome web store early 2015).
2. Connect Go!Temp to the Chromebook's USB port.
3. Launch Graphical Analysis. Go!Temp will be recognized and will display the live temperature reading.
4. Start data collection, if desired.

NOTE: Vernier products are designed for educational use. Our products are not designed nor are they recommended for any industrial, medical, or commercial process such as life support, patient diagnosis, control of a manufacturing process, or industrial testing of any kind.

Specifications

Range	–20 to 115°C
Maximum temperature tolerated without damage to the sensor	150°C
Resolution	0.07°C
Accuracy	±0.5°C
Response time	4 s (to 90% of full reading in water)

Related Products

Go!Temp Teacher Pack (order code: GT-TP)

The Teacher Pack includes eight Go!Temp USB temperature probes.

***Let's Go! Investigating Temperature* (order code: ELB-TEMP)**

This lab manual contains ten experiments for elementary students using Go!Temp temperature probes. More information is available at www.vernier.com/elb-temp

Go! Link® (order code: GO-LINK)

Go! Link is a single-channel USB interface that connects many Vernier sensors to a computer. More information is available at www.vernier.com/go-link

Go! Motion® (order code: GO-MOT)

Go! Motion is a motion detector that connects directly to a USB port, eliminating the need for an additional interface. More information is available at www.vernier.com/go-mot

Warranty

Vernier warrants this product to be free from defects in materials and workmanship for a period of five years from the date of shipment to the customer. This warranty does not cover damage to the product caused by abuse or improper use.

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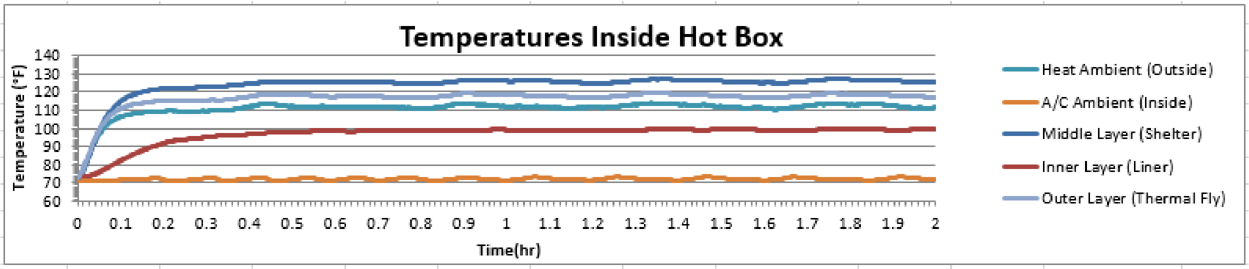
Rev. 12/22/2014

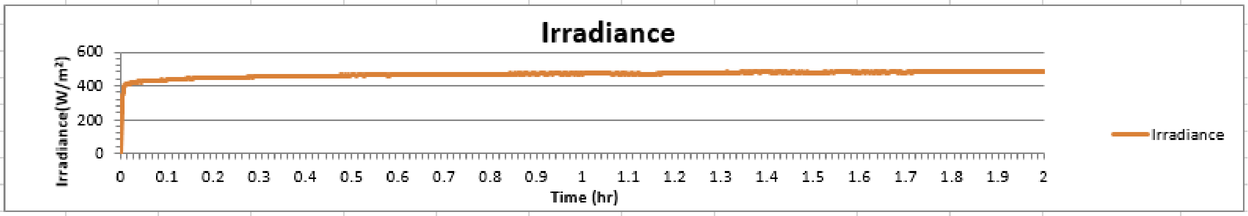
Appendix B. Product descriptions and claims

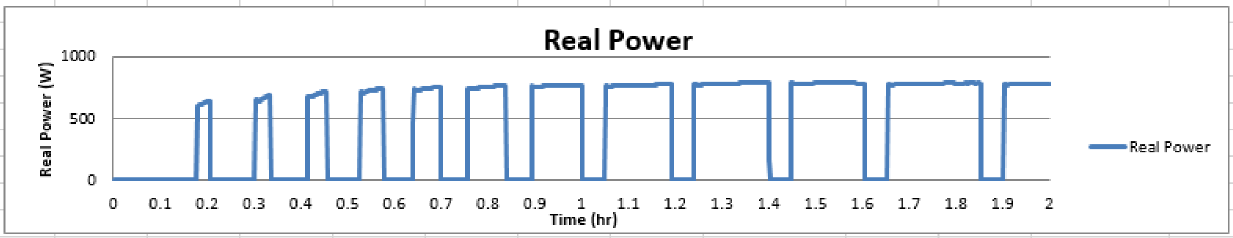
Layer	Designation	RB	Product description and Manufacturer's Claim
Fly	A	No	Single fabric layer, mesh claiming 28% light transmission, 72% shading, 252 openings per square inch
Fly/Skin	B	Yes	Single fabric layer, claiming IR insulation technology
Skin	C	No	Single fabric layer, with no additional IR protection technology
Skin	D	Yes	Single fabric layer, claiming IR insulation using water-based elastomeric fabric coating
Liner	E	Yes	Three layers, batt insulation material between two fabrics, claiming IR protection using semi-crystalline polymers and nitrogen based compounds
Liner	E*	Yes	Three layers, batt insulation material between two fabrics, claiming IR protection using semi-crystalline polymers and nitrogen based compounds
Liner	F	Yes	Three layers, batt insulation material between two fabrics, claiming reflective IR insulation technology with R-Value of 2.64
Liner	G	No	Three layers, batt insulation material between two fabrics, claiming reflective IR insulation technology
Liner	H	No	Three layers, batt insulation material between two fabrics, No additional IR protection technology

Appendix C. Sample hot box results

Table 1: Hot box results





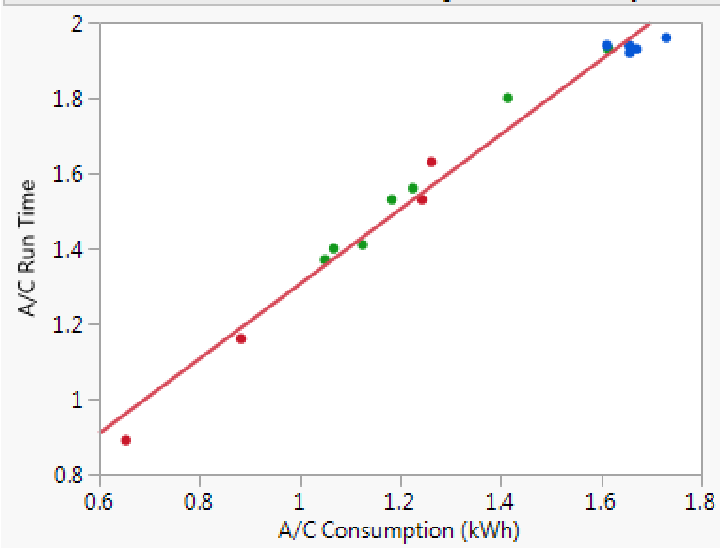


Average Irradiance	466.44	W/m²	Test Time	2	hr
Avg External Temp	110.85	°F	Area	6991	in²
Average Thermal Fly Surface Temp	116.40	°F	A/C Consumption	0.883	kWh
Average Shelter Fabric Surface Temp	123.79	°F	A/C Run Time	1.16	hr
Average Liner Fabric Surface Temp	96.78	°F			
Average Internal Temp	72.02	°F			

Appendix D. Pearson's correlation of A/C runtimes and power consumption

The calculated adjusted Pearson's correlation coefficient between the resulting A/C runtimes and A/C power consumption of the 16 experiments is 0.979.

Bivariate Fit of A/C Run Time By A/C Consumption (kWh)



Linear Fit

Linear Fit

A/C Run Time = 0.313123 + 0.9925892*A/C Consumption (kWh)

Summary of Fit

RSquare	0.980196
RSquare Adj	0.978781
Root Mean Square Error	0.046891
Mean of Response	1.61875
Observations (or Sum Wgts)	16

Analysis of Variance

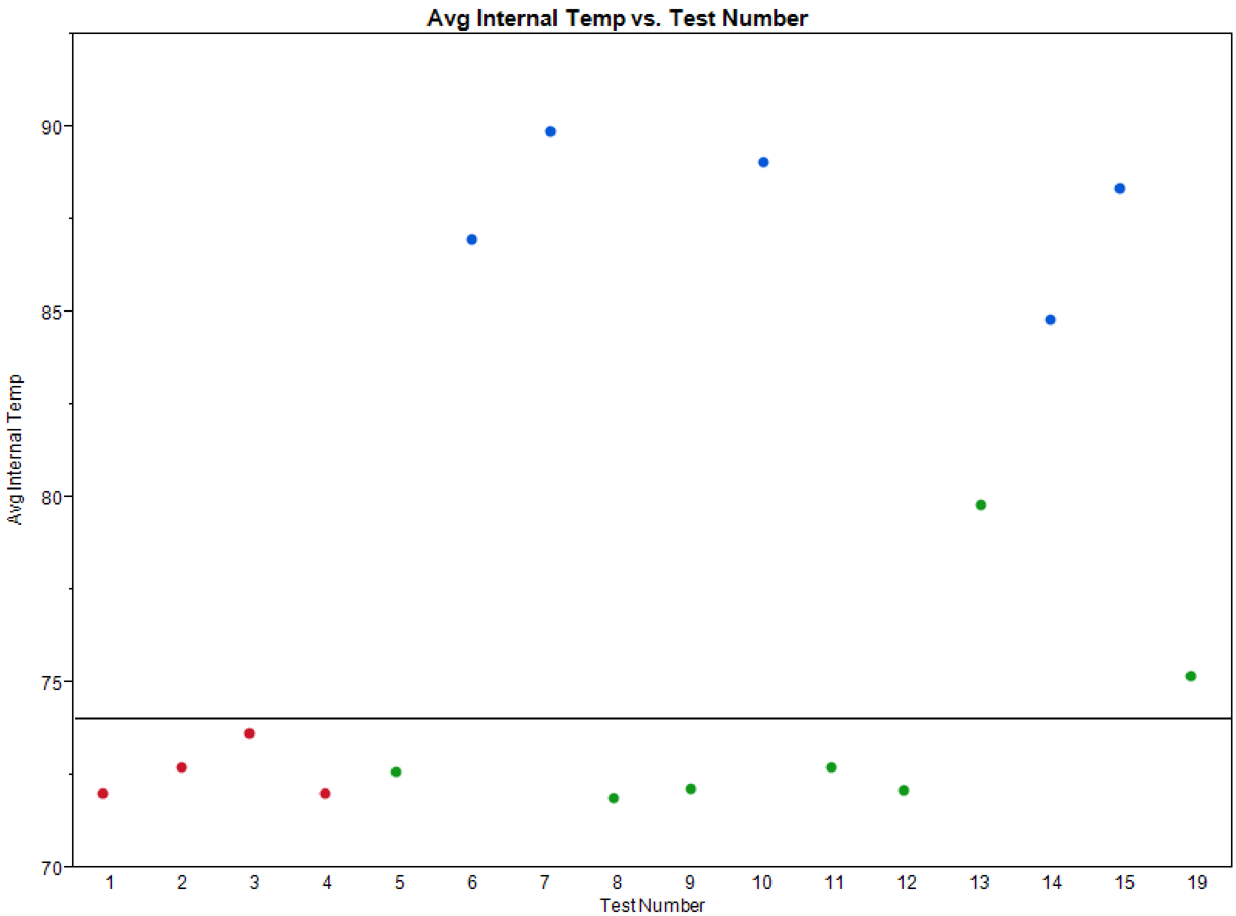
Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	1.5235922	1.52359	692.9284
Error	14	0.0307828	0.00220	Prob > F
C. Total	15	1.5543750		<.0001*

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.313123	0.050966	6.14	<.0001*
A/C Consumption (kWh)	0.9925892	0.037707	26.32	<.0001*

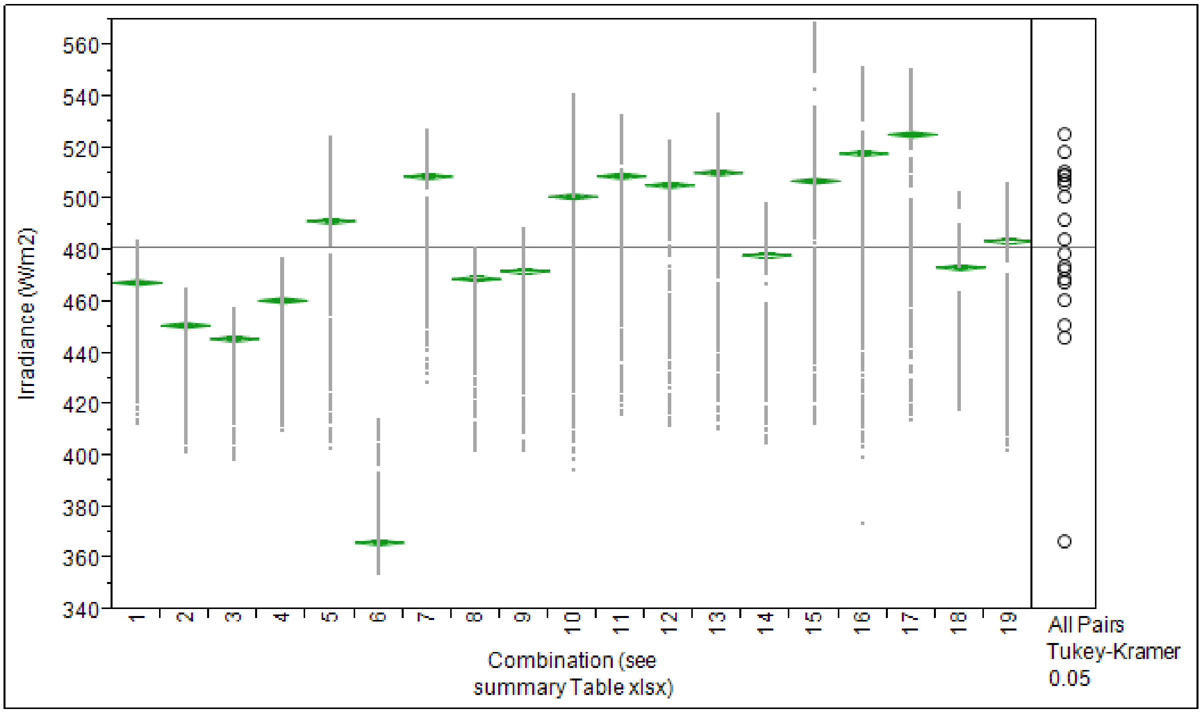
Appendix E. Pass/Fail separation for hot box performance

The 74°*F* indicated by the horizontal line on the graph was a natural separation in the data



Appendix F. Tukey analysis of hot box tests

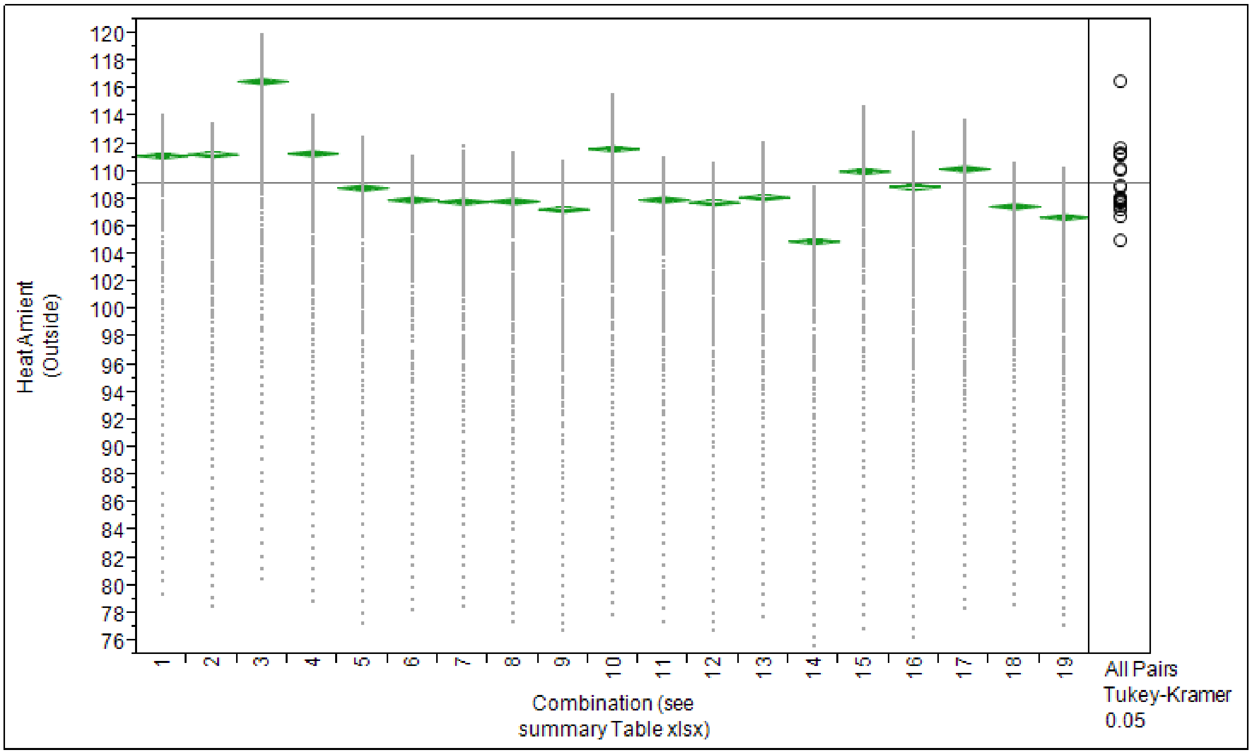
A Tukey analysis for the comparison on means confirmed the only tests not significantly different in terms of both irradiance and exterior temperature are Tests 7, 11, 12, 13, and Test 8, 9.



Connecting Letters Report

Level		Mean
17	A	525.52365
16	B	518.16256
13	C	510.62358
11	C D	509.29692
7	C D	509.14668
15	D E	507.40525
12	E	505.78929
10	F	501.27621
5	G	491.67789
19	H	483.93765
14	I	478.37047
18	J	473.64843
9	J	472.11085
8	K	469.24423
1	K	467.71309
4	L	460.73856
2	M	451.02372
3	N	445.74976
6	O	366.25304

Levels not connected by same letter are significantly different.



Connecting Letters Report

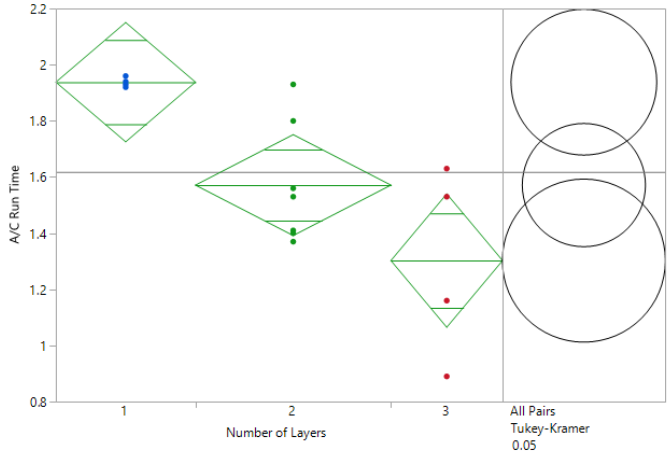
Level										Mean
3	A									116.55990
10		B								111.66858
4		B								111.33562
2		B								111.26592
1		B								111.16611
17			C							110.22456
15			C							110.05675
16				D						108.91204
5				D						108.84255
13					E					108.16305
11					E	F				107.98740
6					E	F				107.97677
8					E	F				107.87705
7					E	F				107.84374
12					E	F	G			107.79321
18						F	G			107.50350
9							G			107.29601
19								H		106.72008
14									I	104.96697

Levels not connected by same letter are significantly different.

Appendix G. Hot box ANOVAs for number of layers and radiant barriers

Hot box

One-way analysis of A/C runtime by Number of layers



Oneway Anova

Summary of Fit

Rsquare	0.59531
Adj Rsquare	0.533049
Root Mean Square Error	0.219972
Mean of Response	1.61875
Observations (or Sum Wgts)	16

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Number of Layers	2	0.9253343	0.462667	9.5617	0.0028*
Error	13	0.6290407	0.048388		
C. Total	15	1.5543750			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
1	5	1.93800	0.09837	1.7255	2.1505
2	7	1.57143	0.08314	1.3918	1.7510
3	4	1.30250	0.10999	1.0649	1.5401

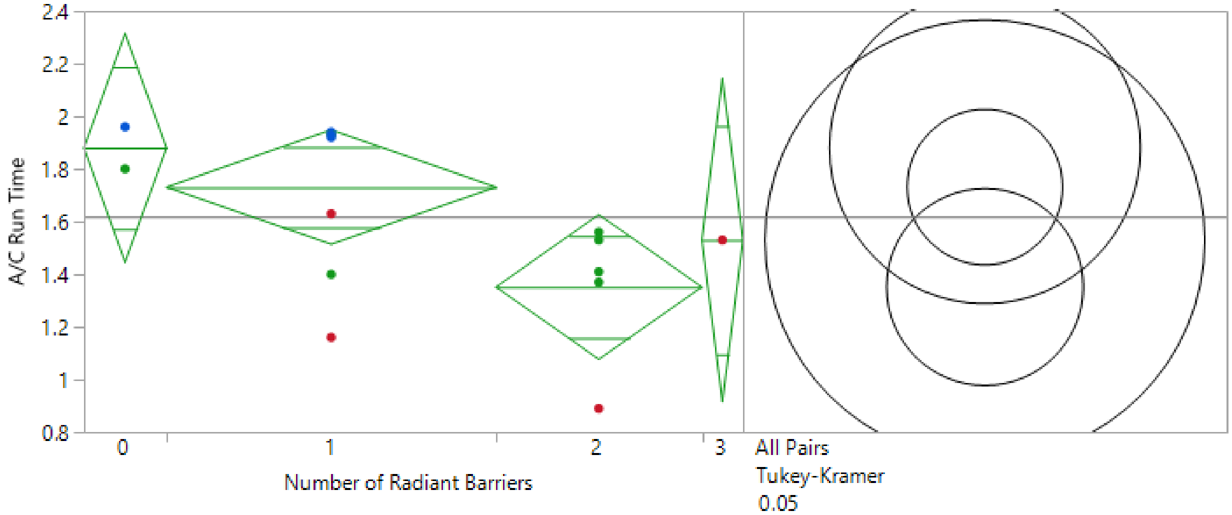
Std Error uses a pooled estimate of error variance

Connecting Letters Report

Level			Mean
1	A		1.9380000
2		B	1.5714286
3		B	1.3025000

Levels not connected by same letter are significantly different.

One-way analysis of A/C runtime by Number of radiant barriers



Oneway Anova

Summary of Fit

Rsquare	0.386913
Adj Rsquare	0.233641
Root Mean Square Error	0.281805
Mean of Response	1.61875
Observations (or Sum Wgts)	16

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Number of Radiant Barriers	3	0.6014075	0.200469	2.5244	0.1070
Error	12	0.9529675	0.079414		
C. Total	15	1.5543750			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
0	2	1.88000	0.19927	1.4458	2.3142
1	8	1.73125	0.09963	1.5142	1.9483
2	5	1.35200	0.12603	1.0774	1.6266
3	1	1.53000	0.28180	0.9160	2.1440

Std Error uses a pooled estimate of error variance

Connecting Letters Report

Level		Mean
0	A	1.8800000
1	A	1.7312500
3	A	1.5300000
2	A	1.3520000

Levels not connected by same letter are significantly different.

Appendix H. MATLAB code for test jigs

The MATLAB® code written by 2Lt Noah Blach condensed the 10 second data in each file into hourly averages, then exported all test days into one excel file

```
                                   code.txt
function Eshleman_Data_Consolidation
format long
Folders={'Test 1','Test 2','Test','Test 4','Test 5','Test 6','Test 7','Test
8','Test 9','Test 0'};  % Test 0 is Test 10, but it is easier to make all the
folder names the same length for parsing
Column_Headers={'Hour','Pyro 1' ,   'Pyro 2'    , 'PWS Temperature'    ,'PWS
Humidity'   ,  'PWS Solar Radiation'   ,  'PWS Wind Speed', ...
    'PWS Wind Direction' ,   'M1 PDP West Watt...' ,    'M1 PDP East Watt...'    'M1
Humidity','Time'...
     'A - LEFT INSIDE'  ,  'A - LEFT LINER'  ,  'A - LEFT INSIDE ...'  ,  'A - LEFT
SKIN' ,   'A - LEFT OUTSIDE...'  ,'A - RIGHT INSIDE'  ,  'A - RIGHT LINER'   , 'A -
RIGHT INSIDE', ...'
 'A - RIGHT SKIN'    , 'A - RIGHT OUTSID...'   , 'E - LEFT INSIDE'  ,  'E - LEFT
LINER' ,   'E - LEFT INSIDE ...' ,   'E - LEFT SKIN' ,   'E - LEFT SPARE' ,   'E -
RIGHT INSIDE', ...
 'E - RIGHT LINER' ,   'E - RIGHT INSIDE...' ,   'E - RIGHT SKIN'    , 'E - RIGHT
SPARE'  ,  'A - LEFT FLY'   , 'A - RIGHT FLY'  ,  'E - LEFT FLY' ,  'E - RIGHT
FLY', ...
'Hour','Dates'};  % Column Headers
tic
for Test_Number= [1 2 5 6 7 8 9 10]  %tests 3 and 4 ommitted
    Weather_Time_Array=[];   Weather_Data=[]; Jig_Time_Array=[];   Jig_Data=[];
     averaged_data=[]; timesearch_used=[];%all data arrays intialized
    Weather_File_Names=ls([Folders{Test_Number} '\M*']);
%pulls names of all weather files
    Jig_File_Names=ls([Folders{Test_Number} '\J*']);
%pulls names of all jig files
    Numfiles_Weather=size(Weather_File_Names,1);
%number of weather files
    Numfiles_Jig=size(Jig_File_Names,1);
%number of jig files
    for n=1:Numfiles_Weather
                                                 %The following is performed for
each weather file in the folder
        A=lvm_import_blach([Folders{Test_Number} '\'
Weather_File_Names(n,1:22)],0);
%imports all data from the lvm formatted file
        Weather_Actual_Date=['20', Weather_File_Names(n,10:11),'/',
Weather_File_Names(n,13:14),'/',Weather_File_Names(n,16:17)];    %The date is
pulled from the file header and formatted with slash marks
        Weather_Time_Array=[Weather_Time_Array;
time_correct(Weather_Actual_Date,A.Segment1.Blach_comment)];
 %  The time data from all files is put in a single array.
        Weather_Data=[Weather_Data; A.Segment1.data(:,60:69)];
                                               %The data from all files is put into
a single array, Weather_data
    end
for n=1:Numfiles_Jig %The following is performed for each weather file in the
                                    Page 1
```

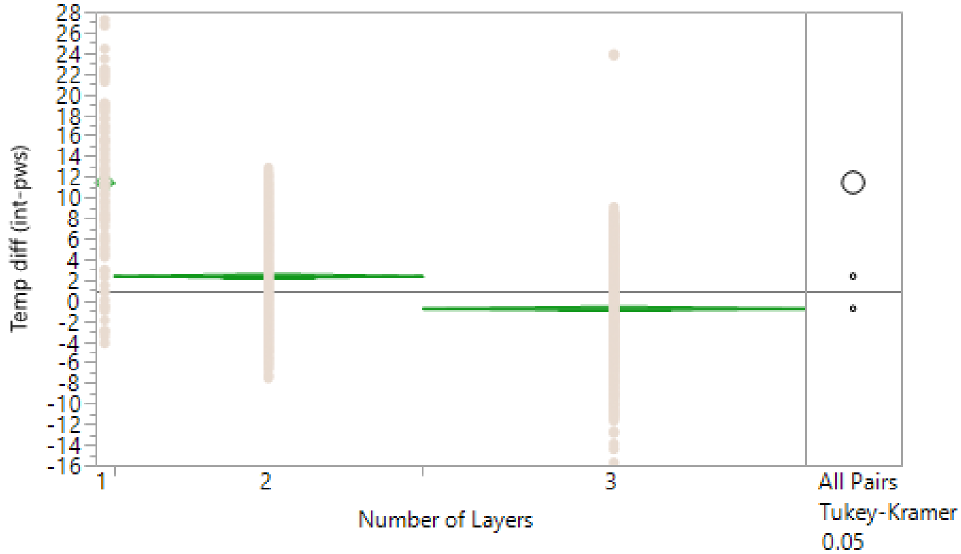
```
folder
    A=lvm_import_blach([Folders{Test_Number} '\'
Jig_File_Names(n,1:17)],0);%imports all data from the lvm formatted file
    Jig_Time_Array=[Jig_Time_Array;
time_correct(A.Segment1.date_lvm{1},A.Segment1.Blach_comment)]; %  The time data
from all files is put in a single array.
    Jig_Data=[Jig_Data; A.Segment1.data(:,[1:10 53:62 105:108])]; %The data from
all files is put into a single array, Jig_data
end
Test_Start_Time=min([Jig_Time_Array; Weather_Time_Array]);  %The first timestamp
found over all the weather and jig files.  The timestamps here are in days since
1/1/0000.
Test_Start_Fractional_Hours=mod(Test_Start_Time,1);      %The fractional hour the
test is starting on.  For example, if the first time is 54321.65 hours since
1/1/0000, this will return .65 hours
Test_End_Time=max([Jig_Time_Array ;Weather_Time_Array]);    %The last timestamp
found over all the weather and jig files.  The timestamps here are in days since
1/1/0000.
Test_Duration=Test_End_Time-Test_Start_Time;                 %The Time difference,
in days between the first and last time found
Weather_Data=[Weather_Data (Weather_Time_Array-Test_Start_Time)];  %Adds a Column
for hours since test start
for timesearch=(Test_Start_Time-Test_Start_Fractional_Hours+.5):1:Test_End_Time   %
starts on the half hour, in one hour increments
    weather_indices=( Weather_Time_Array>(timesearch-.5) &
Weather_Time_Array<(timesearch+.5 ));  %finds all weather times within one half
hour of the searching time (so would search from 0200 to 0300 for a center time of
0230
      jig_indices=( Jig_Time_Array>(timesearch-.5) & Jig_Time_Array<(timesearch+.5
));  % same for jig times
      if(sum(weather_indices)>354 && sum(jig_indices)>354)  %if there are more than
entries in each weather and jig data (no more than one missing minute), proceeds
          timesearch_used=[timesearch_used timesearch];     % adds this time to the
list of times that are used
          weather_start=find(Weather_Time_Array>timesearch-.5,1);  %starting
weather index for this search

weather_end=size(Weather_Time_Array,1)+1-find(flipud(Weather_Time_Array)<timesearch
+.5,1);   %ending weather index for this search
          jig_start=find(Jig_Time_Array>timesearch-.5,1);  %starting jig index for
this search

jig_end=size(Jig_Time_Array,1)+1-find(flipud(Jig_Time_Array)<timesearch+.5,1);
%ending jig index for this search
          averaged_data_temp=[mod(timesearch,24),...
              sum(Weather_Data(weather_start:weather_end,:))/sum(weather_indices),
...  %averages the jig and weather data seperately, then combines them
horizontally, adding a timestamp
```

```
                sum(Jig_Data(jig_start:jig_end,:))/sum(jig_indices), ...
                mod(timesearch,24)];
        averaged_data=[averaged_data ;averaged_data_temp];  %adds this data to the
previously averaged data
        end
end
dates_of_samples=mat2cell(datestr((timesearch_used)/24,'mm/dd/yy'),ones(1,size(time
search_used,2)),8);  %adds a date for each timestamp
xlswrite('Averaged_data_3',Column_Headers,Folders{Test_Number},'A1');  %column
headers
xlswrite('Averaged_data_3',averaged_data,Folders{Test_Number},'A2') ;  %all data
but dates
xlswrite('Averaged_data_3',dates_of_samples,Folders{Test_Number},'AL2') ;  %dates
display('DONE!!!!');
toc
end
return
function time_in_days=time_correct(starting_day,list_of_times )  %returns hours
since 01/01/0000, taking into account a starting day and a list of 24 hour times,
which may go over 0000 of a day.
time_in_days=24*datenum(strcat(starting_day,list_of_times) ,'yyyy/mm/ddHH:MM:SS');
[Y,I] = min(time_in_days);
if(I >1)
time_in_days=time_in_days+24*((1:size(list_of_times,1))>=I)';
end
return
```

Appendix I. Test jig ANOVAs for number of layers and radiant barriers

Test Jig

One-way analysis of Temperature difference by Number of layers



Oneway Anova

Summary of Fit

Rsquare	0.217529
Adj Rsquare	0.217098
Root Mean Square Error	4.392121
Mean of Response	0.889956
Observations (or Sum Wgts)	3639

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Number of Layers	2	19499.353	9749.68	505.4075	<.0001*
Error	3636	70141.078	19.29		
C. Total	3638	89640.431			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
1	95	11.430	0.45062	10.55	12.31
2	1584	2.347	0.11036	2.13	2.56
3	1960	-0.798	0.09921	-0.99	-0.60

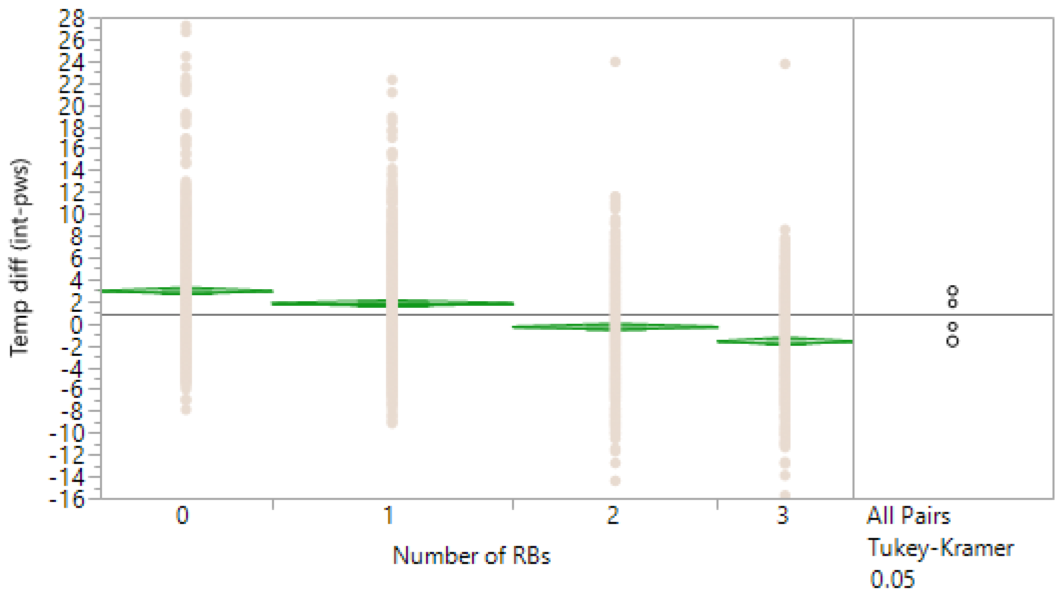
Std Error uses a pooled estimate of error variance

Connecting Letters Report

Level				Mean
1	A			11.42984
2		B		2.34658
3			C	-0.79809

Levels not connected by same letter are significantly different.

One-way analysis of Temperature difference by Number of radiant barriers



Oneway Anova

Summary of Fit

Rsquare	0.111971
Adj Rsquare	0.111238
Root Mean Square Error	4.679651
Mean of Response	0.889956
Observations (or Sum Wgts)	3639

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Number of RBs	3	10037.093	3345.70	152.7777	<.0001*
Error	3635	79603.338	21.90		
C. Total	3638	89640.431			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
0	831	2.9497	0.16234	2.631	3.268
1	1165	1.8278	0.13710	1.559	2.097
2	989	-0.2858	0.14880	-0.578	0.00591
3	654	-1.6198	0.18299	-1.979	-1.261

Std Error uses a pooled estimate of error variance

Connecting Letters Report

Level					Mean
0	A				2.949708
1		B			1.827812
2			C		-0.285841
3				D	-1.619817

Levels not connected by same letter are significantly different.

Appendix J. Statistical analysis for test jig model building

Statistical analysis for model building: This appendix provides information on the creation and testing of each model used for the “Modeling of jig performance” section in Chapter 4 along with the statistical tests performed.

Each model was created using the following steps:

- Stepwise to create model
- ANOVA
- *Test for Normality (Shapiro-Wilk test)*
- *Test for Constant Variance (Breusch-Pagan test)*
- *Test for Independence (Runs Plot)*
- *Test for Outliers (Studentized Residuals Histogram)*
- *Test for Overly Influential Points (Cook's D)*

Model Validity Summary Table

Test Name	Model Adj R-Square	Model Error (Mean APE)	*Test for Normality (S-W)*	*Test for Constant Variance (B-P)*	*Test for Independence (Runs Plot)*
1-A	0.823819	3.8	0.39/pass	0.05/pass	Time series data is auto-correlated and not independent of time. Potentially higher Adjusted R-square is sacrificed by not using finite distributed lag model which would diminish the practical usefulness of model. Researcher acknowledges the increased risk of Type 1 error.
2-A	0.778443	2.9	0.69/pass	0.92/pass	
5-A	0.84179	2.7	0.42/pass	0.45/pass	
6-A	0.888017	3.4	Visual pass	Visual pass	
7-A	0.91684	3.2	0.17/pass	0.94/pass	
8-A	0.908089	4.3	0.25/pass	Visual pass	
9-A	0.818329	3.2	0.21/pass	0.79/pass	
10-A	0.883806	3.8	0.85/pass	0.12/pass	

Linear equation for each model (test-jig)

1-A: $\hat{y} = -94.16859 + 2.1351509\, X_1 + 0.0102784\, X_3$

2-A: $\hat{y} = 17.463574 + 0.6746456\, X_1 + 1.0039456\, X_4 + 0.0353035\, X_5$

5-A: $\hat{y} = -11.94895 + 1.1708007\, X_1 - 0.065094\, X_2 - 0.007483\, X_3 + 0.4214882\, X_4 + 0.0182042\, X_5$

6-A: $\hat{y} = -7.160966 + 1.1621758\, X_1 - 0.07002\, X_2 - 0.00679\, X_3 + 0.1215502\, X_4 + 0.0189657\, X_5$

7-A: $\hat{y} = -3.865584 + 1.1541796\, X_1 - 0.124578\, X_2 - 0.018952\, X_3 + 0.7746298\, X_4 + 0.0191295\, X_5$

8-A: $\hat{y} = -5.968846 + 1.0578358\, X_1 - 0.008782\, X_3 + 0.3107836\, X_4 + 0.0106558\, X_5$

9-A: $\hat{y} = -12.42792 + 1.1590638\, X_1 - 0.007294\, X_3 + 1.1082784\, X_4$

10-A: $\hat{y} = -19.1909 + 1.3011764\, X_1 - 0.049193\, X_2 + 0.0026807\, X_3 + 0.0182042\, X_5$

J-1 Test 1 – A Model building and testing.

<u>Create a Linear Regression Model using stepwise with 80% of data randomly selected</u>

Summary of Fit

RSquare	0.834183
RSquare Adj	0.823819
Root Mean Square Error	3.593317
Mean of Response	97.31118
Observations (or Sum Wgts)	35

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	2	2078.6110	1039.31	80.4919
Error	32	413.1816	12.91	**Prob > F**
C. Total	34	2491.7925		<.0001*

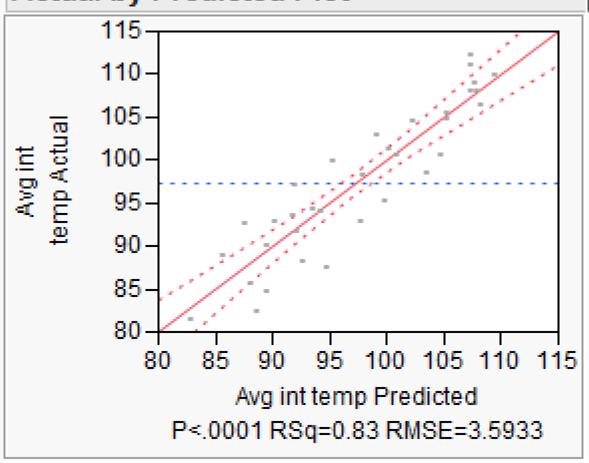
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|	Std Beta	VIF
Intercept	-94.16859	47.6837	-1.97	0.0570	0	.
PWS Temperature	2.1351509	0.563117	3.79	0.0006*	0.567527	4.3234917
PWS Solar Radiation	0.0102784	0.004113	2.50	0.0178*	0.374016	4.3234917

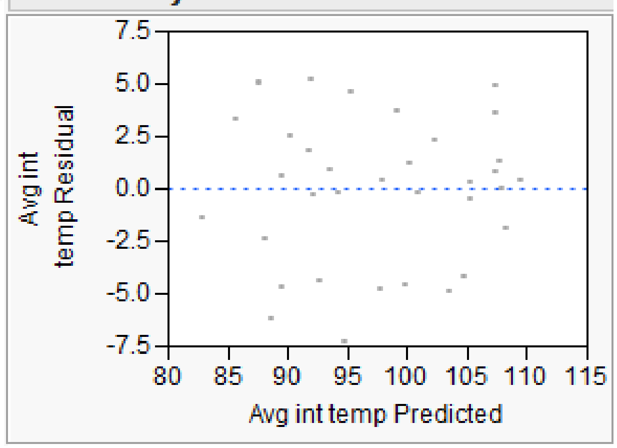
Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
PWS Temperature	1	1	185.63096	14.3767	0.0006*
PWS Solar Radiation	1	1	80.62255	6.2440	0.0178*

Actual by Predicted Plot



Residual by Predicted Plot



Analysis of Variance (ANOVA) to test effects of chosen variables

Test 1: an overall F-test to see if there is an effect, $p<0.05$, one of the variables explains the variability

Ho: NONE of the factors explain variability

Ha: AT LEAST ONE of the factors explains variability

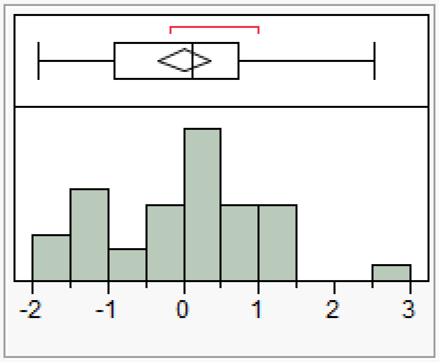
Test 2: Interaction Effect Test to see if combination of variables causes the effect. Ensure VIF score <5 to prevent multicollinearity (if VIF>5, one of the variables must be removed).

Test for Outliers

- Studentized Residuals Histogram Analysis

Distributions

Studentized Resid Avg int temp



Quantiles

100.0%	maximum	2.5435
99.5%		2.5435
97.5%		2.5435
90.0%		1.26619
75.0%	quartile	0.71322
50.0%	median	0.10491
25.0%	quartile	-0.9149
10.0%		-1.3593
2.5%		-1.9223
0.5%		-1.9223
0.0%	minimum	-1.9223

Summary Statistics

Mean	0.0017006
Std Dev	1.0175871
Std Err Mean	0.1672903
Upper 95% Mean	0.340981
Lower 95% Mean	-0.33758
N	37
Range	4.4658094

If Normal:

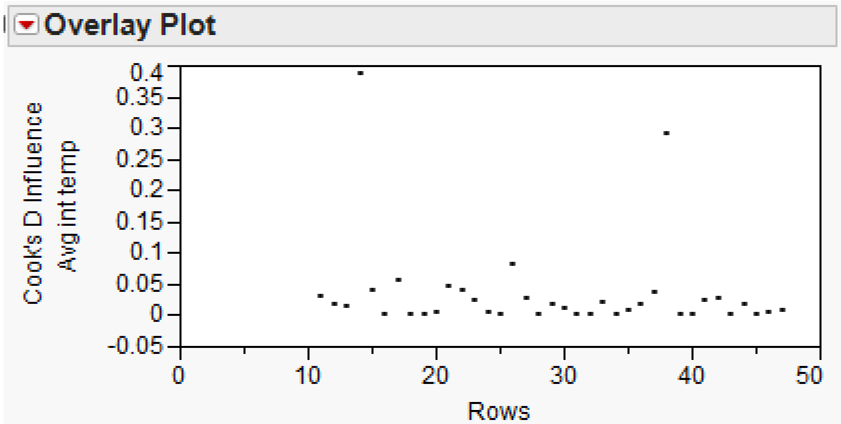
- 99.7% of normalized residuals should be within +/- 3 S.D.s

- 95% of normalized residuals should be within +/- 2 S.D.s

* Removed data point on 10/13/2015 at hour 7.5 as it was flagged as an outlier and overly influential

Test for Overly-Influential Data points

-Ensure no points are outside of 0.5



*Excluded data point on 08/12/2015 at 15.5 hours as an outlier

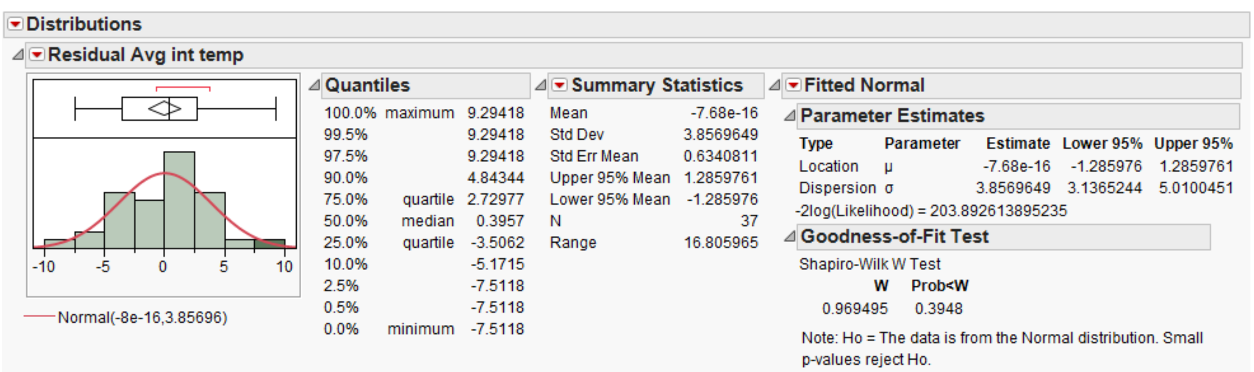
*Excluded data point on 08/11/2015 at 7.5 hours as an outlier

14-38

Test assumptions of the empirical rule

Test for Normality

Using Shapiro-Wilks test for goodness-of-fit



Quantiles

100.0%	maximum	9.29418
99.5%		9.29418
97.5%		9.29418
90.0%		4.84344
75.0%	quartile	2.72977
50.0%	median	0.3957
25.0%	quartile	-3.5062
10.0%		-5.1715
2.5%		-7.5118
0.5%		-7.5118
0.0%	minimum	-7.5118

Summary Statistics

Mean	-7.68e-16
Std Dev	3.8569649
Std Err Mean	0.6340811
Upper 95% Mean	1.2859761
Lower 95% Mean	-1.285976
N	37
Range	16.805965

Fitted Normal

Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Location	μ	-7.68e-16	-1.285976	1.2859761
Dispersion	σ	3.8569649	3.1365244	5.0100451

-2log(Likelihood) = 203.892613895235

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.969495	0.3948

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Test for Constant Variance

Breusch-Pagan Test

Ho: Residuals have Constant Variance

Ha: Residuals do NOT have constant Variance

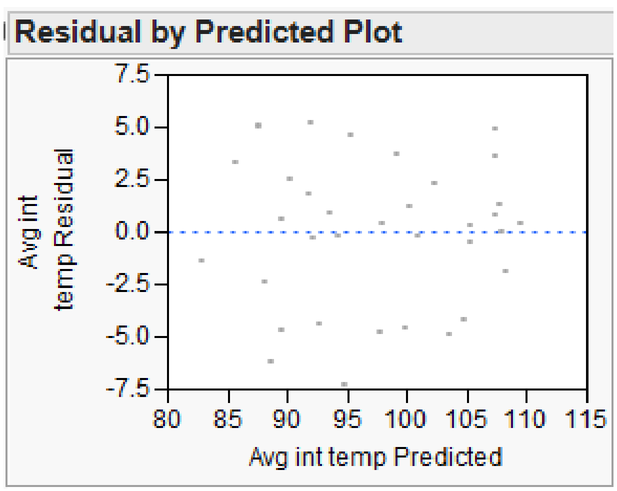
Breusch-Pagan Test

N	35
df(Exp)	2
SSE	413.1816
SSR	1668.946

T.S.	**5.987789**
Pvalue	**0.050092**

Reject the null hypothesis: residuals DO NOT have constant variance

Visually inspect residual by predicted plot

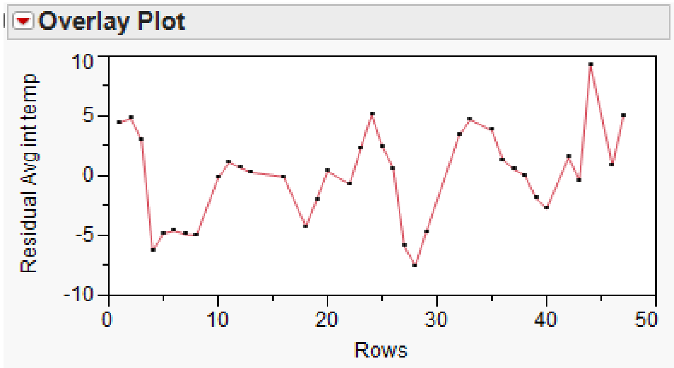


-See if it Vs out or in and compare the majority grouping top and bottom range to the extreme top and bottom range. If the extreme range is less than 2x the majority grouping range, this is a "Soft" Fail. Continue on.

Testing for Independence

- Non-ordered data (observational) looking for trends over time. No Trends means residuals are independent over time

*Not all days shown, but representative of test period



Usefulness of Model

Mean Absolute Percent Error

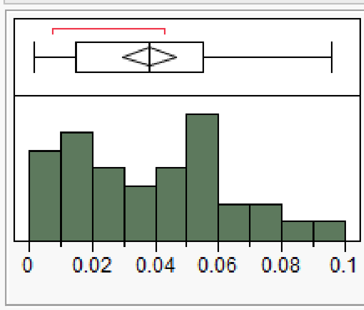
Absolute value of what the model observed (or actual), minus the predicted, all divided by observed

$$\frac{|y-\dot{y}|}{y}\times 100\%$$

Working Set (random 80% of data)

Distributions

Mean APE



Quantiles

100.0%	maximum	0.09573
99.5%		0.09573
97.5%		0.09573
90.0%		0.07096
75.0%	quartile	0.05515
50.0%	median	0.03822
25.0%	quartile	0.01486
10.0%		0.00775
2.5%		0.00157
0.5%		0.00157
0.0%	minimum	0.00157

Summary Statistics

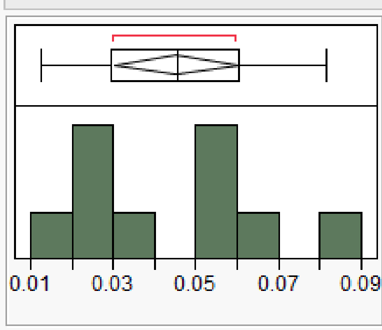
Mean	0.0380233
Std Dev	0.0241696
Std Err Mean	0.0040854
Upper 95% Mean	0.0463258
Lower 95% Mean	0.0297208
N	35
Range	0.0941548

Mean = 0.038 shows a 3.8% error

Validation set (remaining 20% of data)

Distributions

Mean APE



Quantiles

100.0%	maximum	0.08174
99.5%		0.08174
97.5%		0.08174
90.0%		0.07993
75.0%	quartile	0.06046
50.0%	median	0.04559
25.0%	quartile	0.02932
10.0%		0.01381
2.5%		0.01226
0.5%		0.01226
0.0%	minimum	0.01226

Summary Statistics

Mean	0.0453184
Std Dev	0.0213491
Std Err Mean	0.0067512
Upper 95% Mean	0.0605906
Lower 95% Mean	0.0300461
N	10
Range	0.0694776

Mean = 0.045 shows a 4.5% error

Model Equation

$$\hat{y} = -94.16859 + 2.1351509\, X_1 + 0.0102784\, X_3$$

- $\hat{y}$ = internal temperature of jig
- X_1= Temp
- X_2= Humidity
- X_3= Solar Radiation
- X_4= Wind Speed
- X_5= Wind Direction

J-2 Test 2 – A Model building and testing

<u>Create a Linear Regression Model using stepwise with 80% of data randomly selected</u>

Summary of Fit

RSquare	0.796907
RSquare Adj	0.778443
Root Mean Square Error	3.049557
Mean of Response	84.36954
Observations (or Sum Wgts)	37

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	3	1204.2009	401.400	43.1623
Error	33	306.8934	9.300	**Prob > F**
C. Total	36	1511.0943		<.0001*

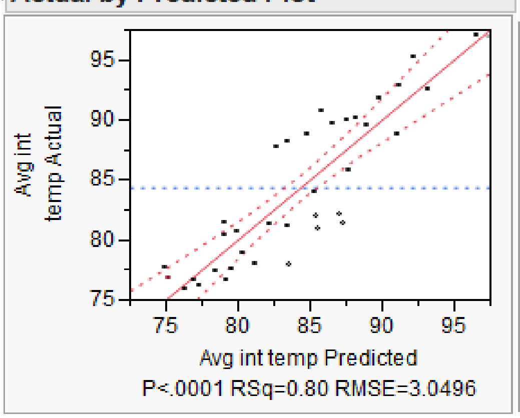
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|	Std Beta	VIF
Intercept	17.463574	9.459048	1.85	0.0738	0	.
PWS Temperature	0.6746456	0.1211	5.57	<.0001*	0.523393	1.4342035
PWS Wind Speed	1.0039456	0.464732	2.16	0.0381*	0.264568	2.4371235
PWS Wind Direction	0.0353035	0.014113	2.50	0.0175*	0.279357	2.026469

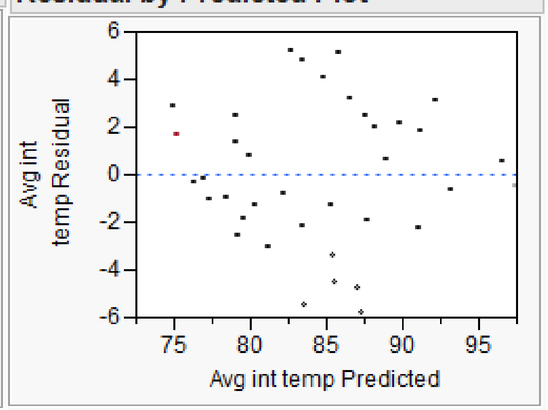
Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
PWS Temperature	1	1	288.62664	31.0358	<.0001*
PWS Wind Speed	1	1	43.39998	4.6668	0.0381*
PWS Wind Direction	1	1	58.19282	6.2574	0.0175*

Actual by Predicted Plot



Residual by Predicted Plot



Analysis of Variance (ANOVA) to test effects of chosen variables

Test 1: an overall F-test to see if there is an effect, $p<0.05$, one of the variables explains the variability

Ho: NONE of the factors explain variability

Ha: AT LEAST ONE of the factors explains variability

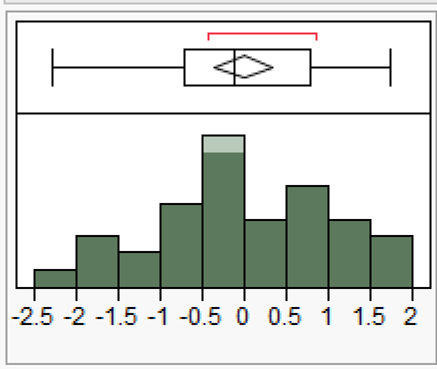
Test 2: Interaction Effect Test to see if combination of variables causes the effect. Ensure VIF score <5 to prevent multicollinearity (if VIF>5, one of the variables must be removed).

Test for Outliers

- Studentized Residuals Histogram Analysis

Distributions

Studentized Resid Avg int temp



Quantiles

100.0%	maximum	1.73701
99.5%		1.73701
97.5%		1.73701
90.0%		1.40783
75.0%	quartile	0.78066
50.0%	median	-0.1206
25.0%	quartile	-0.7166
10.0%		-1.5643
2.5%		-2.2987
0.5%		-2.2987
0.0%	minimum	-2.2987

Summary Statistics

Mean	-0.009706
Std Dev	1.0134291
Std Err Mean	0.1666067
Upper 95% Mean	0.3281878
Lower 95% Mean	-0.3476
N	37
Range	4.0357436

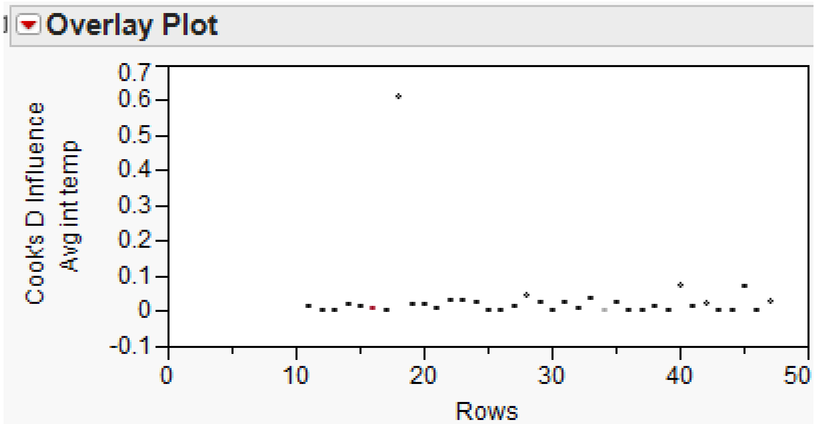
If Normal:

- 99.7% of normalized residuals should be within +/- 3 S.D.s

- 95% of normalized residuals should be within +/- 2 S.D.s

Test for Overly-Influential Data points

-Ensure no points are outside of 0.5

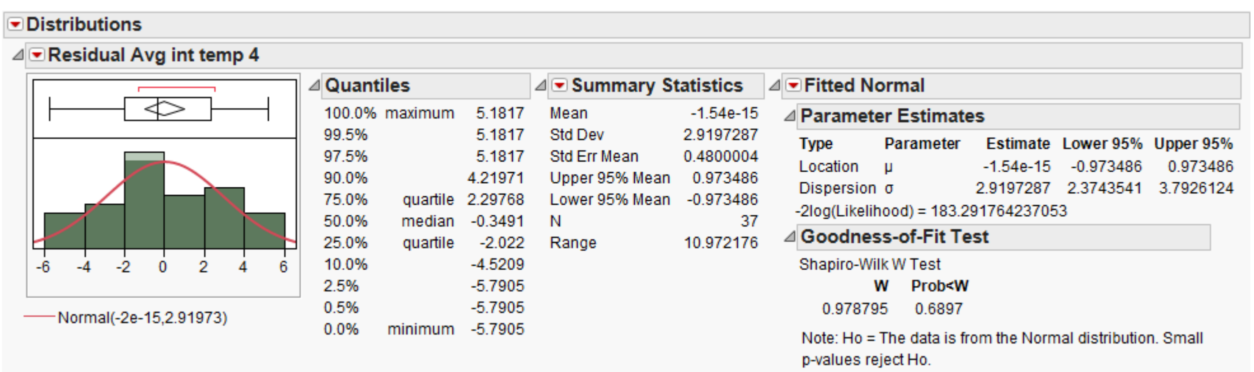


One point excluded as overly-influential

Test assumptions of the empirical rule

Test for Normality

Using Shapiro-Wilks test for goodness-of-fit



Fail to reject the null hypothesis: residuals are normally distributed

Test for Constant Variance

Breusch-Pagan Test

Ho: Residuals have Constant Variance

Ha: Residuals do NOT have constant Variance

Breusch-Pagan Test

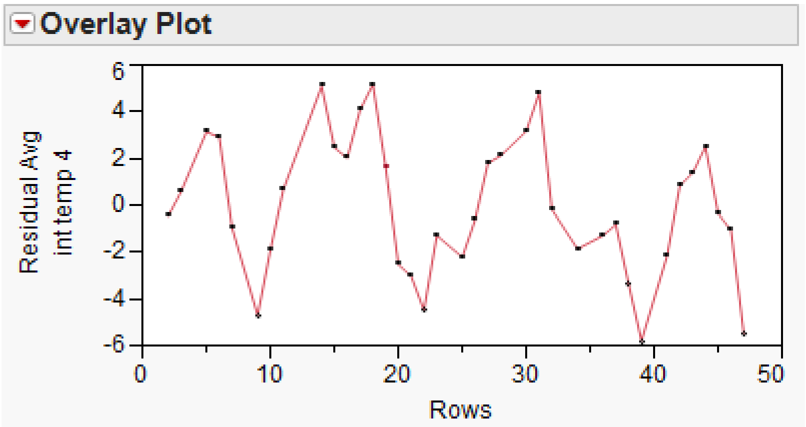
N	37
df(Exp)	3
SSE	306.8934
SSR	69.3925

T.S.	**0.5043255**
Pvalue	**0.9179401**

Fail to reject the null hypothesis: residuals have constant variance

Testing for Independence

- Non-ordered data (observational) looking for trends over time. No Trends means residuals are independent over time



Usefulness of Model

Mean Absolute Percent Error

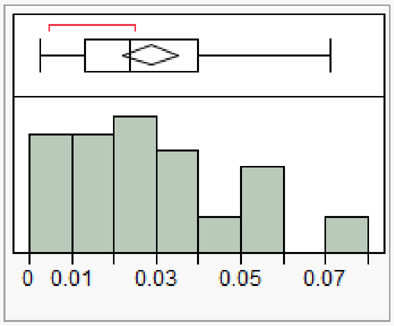
Absolute value of what the model observed (or actual), minus the predicted, all divided by observed

$$\frac{|y-\dot{y}|}{y}\times 100\%$$

Working Set (random 80% of data)

Distributions

Mean APE



Quantiles

100.0%	maximum	0.07105
99.5%		0.07105
97.5%		0.07105
90.0%		0.05754
75.0%	quartile	0.03989
50.0%	median	0.02383
25.0%	quartile	0.01313
10.0%		0.00571
2.5%		0.00231
0.5%		0.00231
0.0%	minimum	0.00231

Summary Statistics

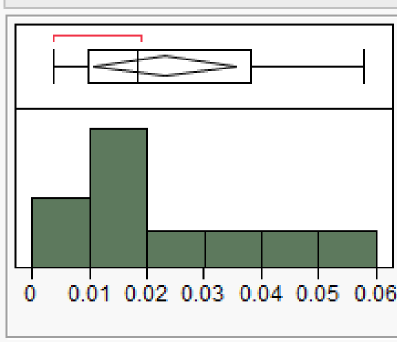
Mean	0.0285461
Std Dev	0.0192379
Std Err Mean	0.0031627
Upper 95% Mean	0.0349603
Lower 95% Mean	0.0221319
N	37
Range	0.068748

Mean = 0.029 shows a 2.9% error

Validation set (remaining 20% of data)

Distributions

Mean APE



Quantiles

100.0%	maximum	0.05793
99.5%		0.05793
97.5%		0.05793
90.0%		0.05644
75.0%	quartile	0.03809
50.0%	median	0.01838
25.0%	quartile	0.00972
10.0%		0.0038
2.5%		0.00361
0.5%		0.00361
0.0%	minimum	0.00361

Summary Statistics

Mean	0.0231549
Std Dev	0.0174793
Std Err Mean	0.0055274
Upper 95% Mean	0.0356588
Lower 95% Mean	0.0106509
N	10
Range	0.0543232

Mean = 0.023 shows a 2.3% error

Model Equation

$$\hat{y} = 17.463574 + 0.6746456\,X_1 + 1.0039456\,X_4 + 0.0353035\,X_5$$

- $\hat{y}$ = internal temperature of jig
- X_1= Temp
- X_2= Humidity
- X_3= Solar Radiation
- X_4= Wind Speed
- X_5= Wind Direction

J-3 Test 5 – A Model building and testing.

<u>Create a Linear Regression Model using stepwise with 80% of data randomly selected</u>

Summary of Fit

RSquare	0.846828
RSquare Adj	0.84179
Root Mean Square Error	3.208798
Mean of Response	84.67661
Observations (or Sum Wgts)	158

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	5	8652.579	1730.52	168.0703
Error	152	1565.050	10.30	**Prob > F**
C. Total	157	10217.630		<.0001*

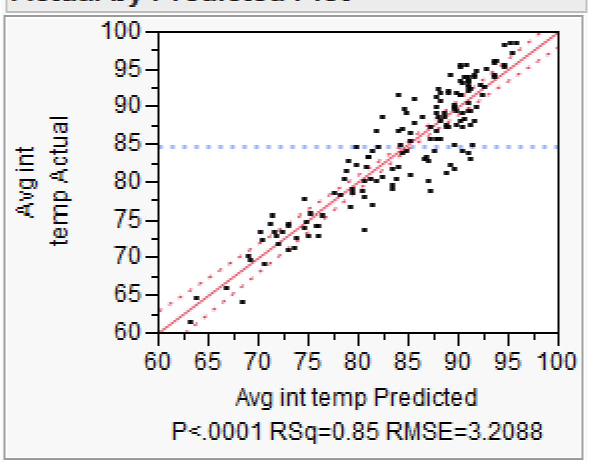
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|	Std Beta	VIF
Intercept	-11.94895	6.188234	-1.93	0.0554	0	.
PWS Temperature	1.1708007	0.066318	17.65	<.0001*	0.816925	2.1248431
PWS Humidity	-0.065094	0.024981	-2.61	0.0101*	-0.11867	2.0581495
PWS Solar Radiation	-0.007483	0.001405	-5.33	<.0001*	-0.24571	2.112486
PWS Wind Speed	0.4214882	0.165625	2.54	0.0119*	0.099363	1.5128436
PWS Wind Direction	0.0182042	0.003288	5.54	<.0001*	0.227483	1.6754104

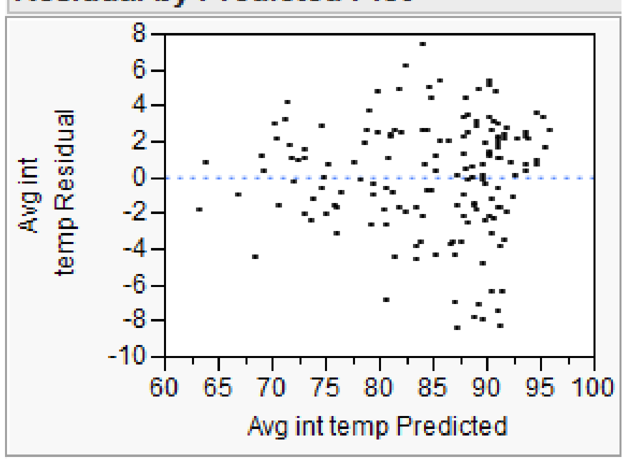
Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
PWS Temperature	1	1	3209.1288	311.6754	<.0001*
PWS Humidity	1	1	69.9086	6.7896	0.0101*
PWS Solar Radiation	1	1	292.0126	28.3607	<.0001*
PWS Wind Speed	1	1	66.6809	6.4762	0.0119*
PWS Wind Direction	1	1	315.5923	30.6508	<.0001*

Actual by Predicted Plot



Residual by Predicted Plot



Analysis of Variance (ANOVA) to test effects of chosen variables

Test 1: an overall F-test to see if there is an effect, $p<0.05$, one of the variables explains the variability

Ho: NONE of the factors explain variability

Ha: AT LEAST ONE of the factors explains variability

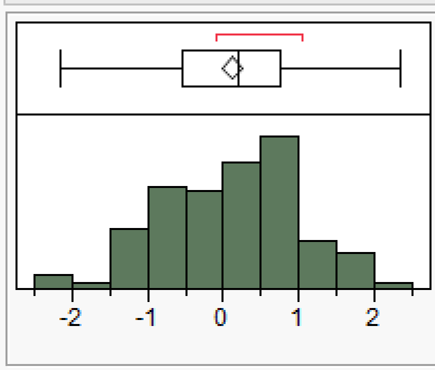
Test 2: Interaction Effect Test to see if combination of variables causes the effect. Ensure VIF score <5 to prevent multicollinearity (if VIF>5, one of the variables must be removed).

Test for Outliers

- Studentized Residuals Histogram Analysis

Distributions

Studentized Resid Avg int temp



Quantiles

100.0%	maximum	2.35635
99.5%		2.35635
97.5%		1.68557
90.0%		1.12714
75.0%	quartile	0.75902
50.0%	median	0.2086
25.0%	quartile	-0.5452
10.0%		-1.1431
2.5%		-1.6318
0.5%		-2.1588
0.0%	minimum	-2.1588

Summary Statistics

Mean	0.1148224
Std Dev	0.8695688
Std Err Mean	0.0707645
Upper 95% Mean	0.2546463
Lower 95% Mean	-0.025002
N	151
Range	4.515146

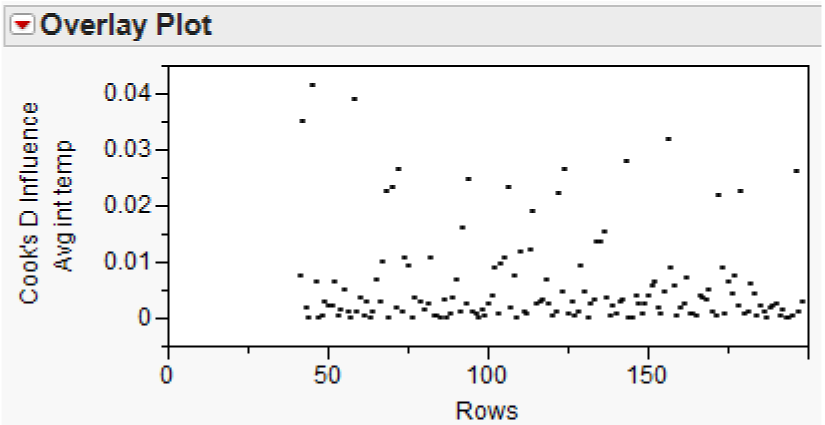
If Normal:

- 99.7% of normalized residuals should be within +/- 3 S.D.s

- 95% of normalized residuals should be within +/- 2 S.D.s

Test for Overly-Influential Data points

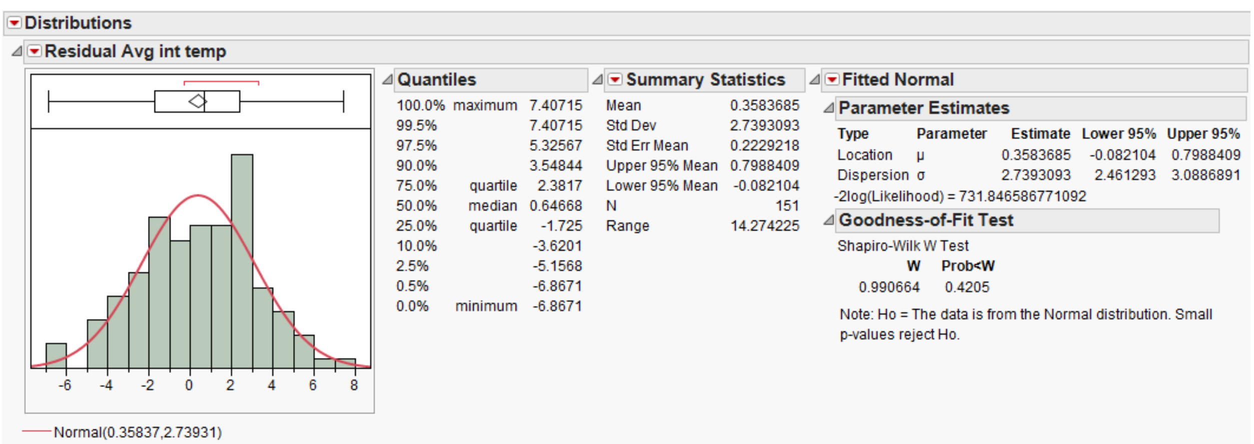
-Ensure no points are outside of 0.5



Test assumptions of the empirical rule

Test for Normality

Using Shapiro-Wilks test for goodness-of-fit



*excluded 7 hours of data to make normal, all data was in the morning hours

Test for Constant Variance

Breusch-Pagan Test

Ho: Residuals have Constant Variance

Ha: Residuals do NOT have constant Variance

Breusch-Pagan Test

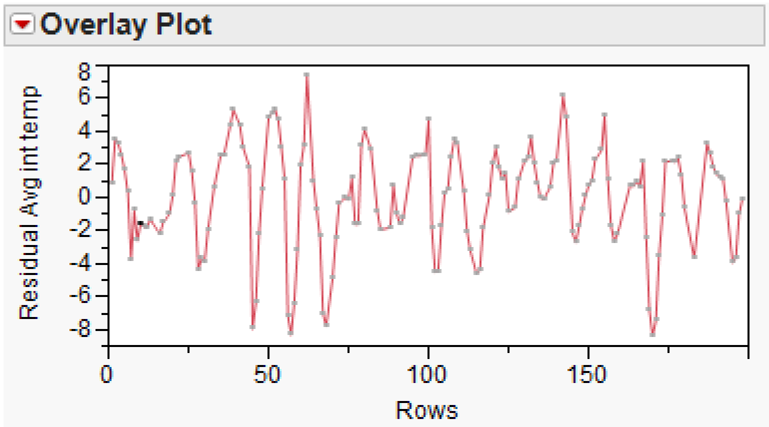
N	158
df(Exp)	5
SSE	1565.05
SSR	928.492

T.S.	**4.731577**
Pvalue	**0.449509**

Fail to reject the null hypothesis: residuals have constant variance

Testing for Independence

- Non-ordered data (observational) looking for trends over time. No Trends means residuals are independent over time



Usefulness of Model

Mean Absolute Percent Error

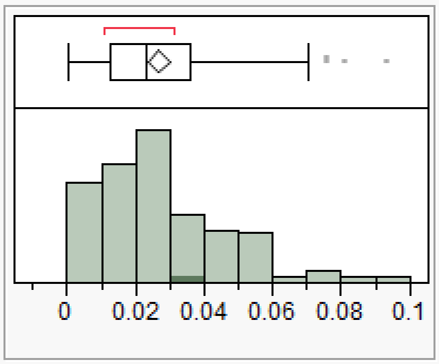
Absolute value of what the model observed (or actual), minus the predicted, all divided by observed

$$\frac{|y-\dot{y}|}{y}\times 100\%$$

Working Set (random 80% of data)

Distributions

Mean APE



Quantiles

100.0%	maximum	0.09317
99.5%		0.09317
97.5%		0.07563
90.0%		0.05452
75.0%	quartile	0.03585
50.0%	median	0.02335
25.0%	quartile	0.01256
10.0%		0.00554
2.5%		0.00066
0.5%		0.00012
0.0%	minimum	0.00012

Summary Statistics

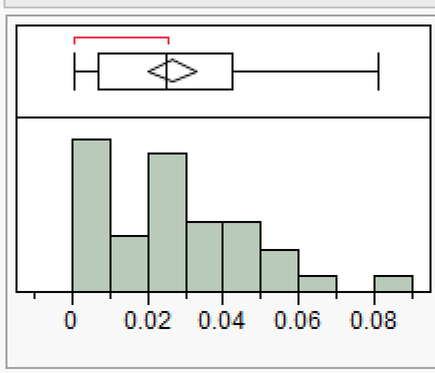
Mean	0.0268549
Std Dev	0.0184523
Std Err Mean	0.0015016
Upper 95% Mean	0.029822
Lower 95% Mean	0.0238878
N	151
Range	0.0930484

Mean = 0.027 shows a 2.7% error

Validation set (remaining 20% of data)

Distributions

Mean APE



Quantiles

100.0%	maximum	0.08135
99.5%		0.08135
97.5%		0.08088
90.0%		0.05383
75.0%	quartile	0.04224
50.0%	median	0.02479
25.0%	quartile	0.00679
10.0%		0.00341
2.5%		0.00038
0.5%		0.00037
0.0%	minimum	0.00037

Summary Statistics

Mean	0.0265695
Std Dev	0.0198593
Std Err Mean	0.00314
Upper 95% Mean	0.0329208
Lower 95% Mean	0.0202182
N	40
Range	0.0809723

Mean = 0.027 shows a 2.7% error

Model Equation

$$\hat{y} = -11.94895 + 1.1708007\,X_1 - 0.065094\,X_2 - 0.007483\,X_3 + 0.4214882\,X_4 + 0.0182042\,X_5$$

- $\hat{y}$ = internal temperature of jig
- X_1= Temp
- X_2= Humidity
- X_3= Solar Radiation
- X_4= Wind Speed
- X_5= Wind Direction

J-4 Test 6 – A Model building and testing.

Create a Linear Regression Model using stepwise with 80% of data randomly selected

Summary of Fit

RSquare	0.889216
RSquare Adj	0.888017
Root Mean Square Error	3.278545
Mean of Response	77.45062
Observations (or Sum Wgts)	468

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	5	39859.695	7971.94	741.6547
Error	462	4965.971	10.75	Prob > F
C. Total	467	44825.666		<.0001*

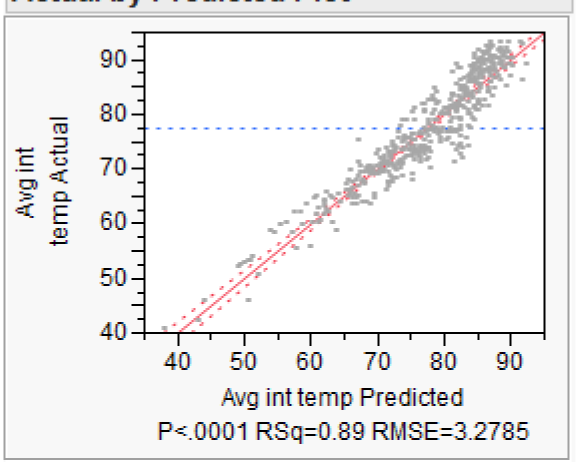
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|	Std Beta	VIF
Intercept	-7.160966	2.195789	-3.26	0.0012*	0	.
PWS Temperature	1.1621758	0.026726	43.49	<.0001*	0.884639	1.7258829
PWS Humidity	-0.07002	0.012908	-5.42	<.0001*	-0.10927	1.6922239
PWS Solar Radiation	-0.00679	0.000931	-7.29	<.0001*	-0.1641	2.1118405
PWS Wind Speed	0.1215502	0.088417	1.37	0.1699	0.023374	1.2055542
PWS Wind Direction	0.0189657	0.002011	9.43	<.0001*	0.171703	1.3829734

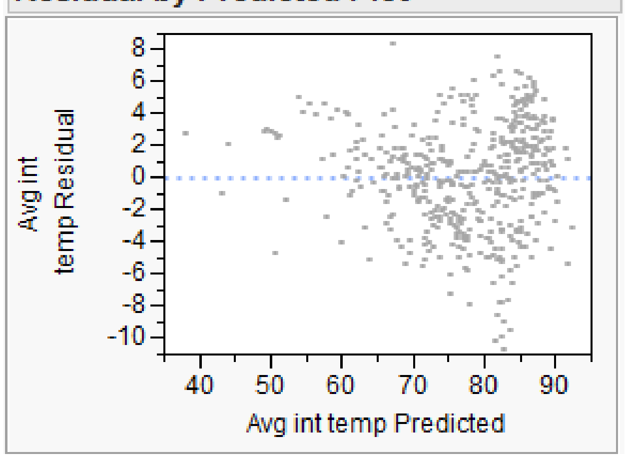
Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
PWS Temperature	1	1	20325.806	1890.974	<.0001*
PWS Humidity	1	1	316.271	29.4237	<.0001*
PWS Solar Radiation	1	1	571.614	53.1791	<.0001*
PWS Wind Speed	1	1	20.314	1.8899	0.1699
PWS Wind Direction	1	1	955.589	88.9014	<.0001*

Actual by Predicted Plot



Residual by Predicted Plot



Analysis of Variance (ANOVA) to test effects of chosen variables

Test 1: an overall F-test to see if there is an effect, $p<0.05$, one of the variables explains the variability

Ho: NONE of the factors explain variability

Ha: AT LEAST ONE of the factors explains variability

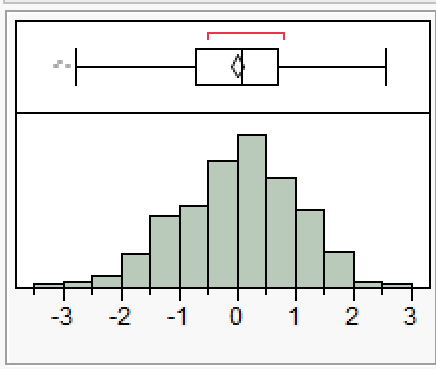
Test 2: Interaction Effect Test to see if combination of variables causes the effect. Ensure VIF score <5 to prevent multicollinearity (if VIF>5, one of the variables must be removed).

Test for Outliers

- Studentized Residuals Histogram Analysis

Distributions

Studentized Resid Avg int temp



Quantiles

100.0%	maximum	2.57022
99.5%		2.22651
97.5%		1.74748
90.0%		1.25112
75.0%	quartile	0.69409
50.0%	median	0.08942
25.0%	quartile	-0.7228
10.0%		-1.3208
2.5%		-2.0159
0.5%		-3.0144
0.0%	minimum	-3.1433

Summary Statistics

Mean	0.0072095
Std Dev	0.9902685
Std Err Mean	0.0458242
Upper 95% Mean	0.097257
Lower 95% Mean	-0.082838
N	467
Range	5.7135285

If Normal:

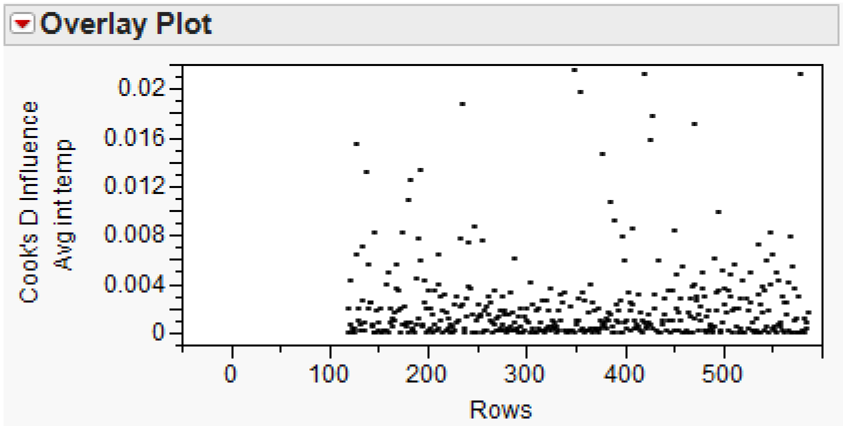
- 99.7% of normalized residuals should be within +/- 3 S.D.s

- 95% of normalized residuals should be within +/- 2 S.D.s

* Removed data point on 10/13/2015 at hour 7.5 as it was flagged as an outlier and overly influential

Test for Overly-Influential Data points

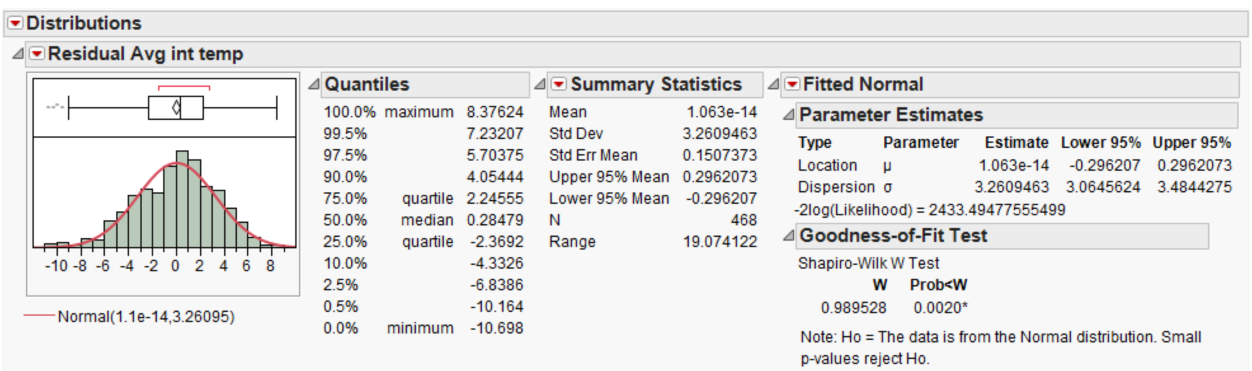
-Ensure no points are outside of 0.5



Test assumptions of the empirical rule

Test for Normality

Using Shapiro-Wilks test for goodness-of-fit



*Fails goodness of fit test but passes visual inspection for normal distribution

Test for Constant Variance

Breusch-Pagan Test

Ho: Residuals have Constant Variance

Ha: Residuals do NOT have constant Variance

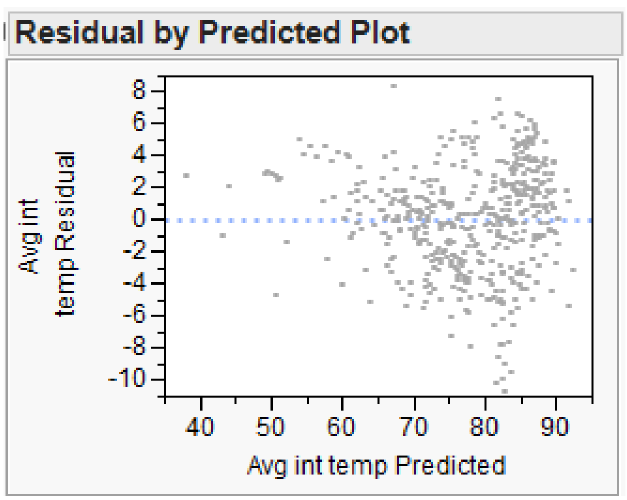
Breusch-Pagan Test

N	468
df(Exp)	5
SSE	4965.971
SSR	3648.887

T.S.	**16.20368**
Pvalue	**0.006286**

Reject the null hypothesis: residuals DO NOT have constant variance

Visually inspect residual by predicted plot

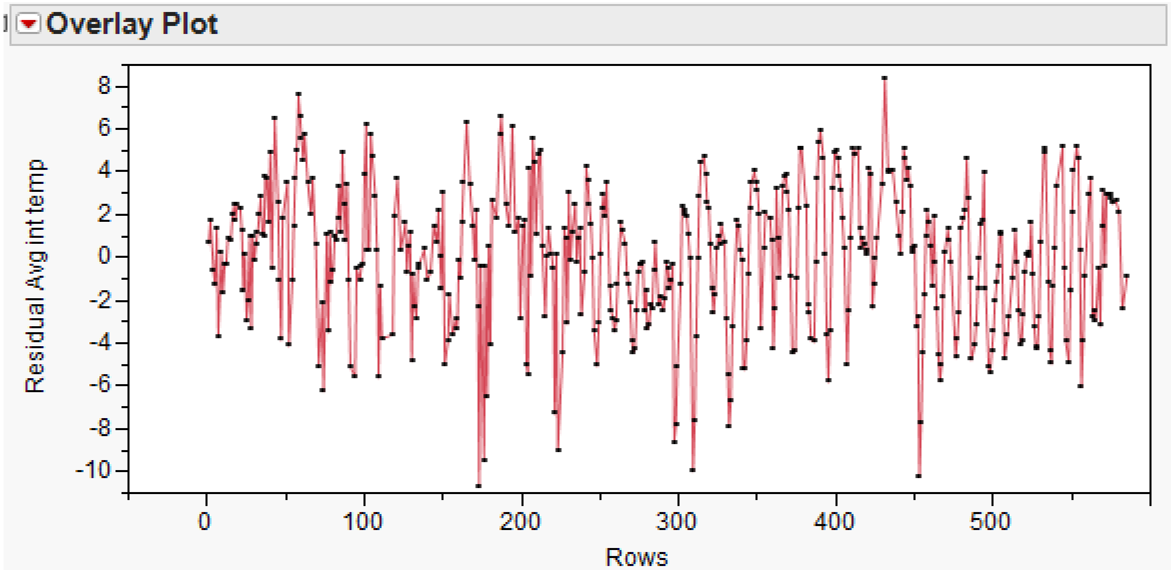


-See if it Vs out or in and compare the majority grouping top and bottom range to the extreme top and bottom range. If the extreme range is less than 2x the majority grouping range, this is a "Soft" Fail. Continue on.

Testing for Independence

- Non-ordered data (observational) looking for trends over time. No Trends means residuals are independent over time

*Not all days shown, but representative of test period



Usefulness of Model

Mean Absolute Percent Error

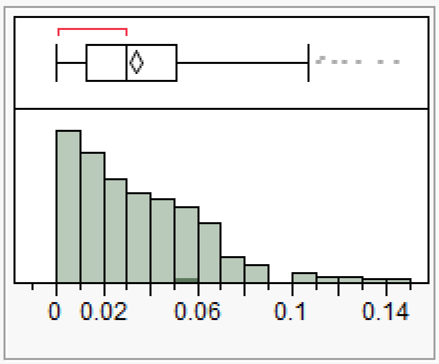
Absolute value of what the model observed (or actual), minus the predicted, all divided by observed

$$\frac{\left|y-\dot{y}\right|}{y}\times 100\%$$

Working Set (random 80% of data)

Distributions

Mean APE



Quantiles

100.0%	maximum	0.14426
99.5%		0.13461
97.5%		0.10202
90.0%		0.0665
75.0%	quartile	0.05062
50.0%	median	0.0293
25.0%	quartile	0.01255
10.0%		0.00469
2.5%		0.00152
0.5%		0.0005
0.0%	minimum	0.00013

Summary Statistics

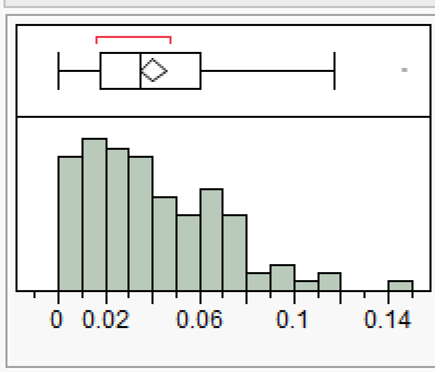
Mean	0.0338224
Std Dev	0.0257267
Std Err Mean	0.0011905
Upper 95% Mean	0.0361617
Lower 95% Mean	0.031483
N	467
Range	0.1441325

Mean = 0.034 shows a 3.4% error

Validation set (remaining 20% of data)

Distributions

Mean APE



Quantiles

100.0%	maximum	0.14691
99.5%		0.14691
97.5%		0.11047
90.0%		0.07417
75.0%	quartile	0.06053
50.0%	median	0.0347
25.0%	quartile	0.0177
10.0%		0.00475
2.5%		0.0016
0.5%		0.00013
0.0%	minimum	0.00013

Summary Statistics

Mean	0.0401988
Std Dev	0.0284014
Std Err Mean	0.0026257
Upper 95% Mean	0.0453994
Lower 95% Mean	0.0349983
N	117
Range	0.1467797

Mean = 0.040 shows a 4.0% error

Model Equation

$$\hat{y} = -7.160966 + 1.1621758\,X_1 - 0.07002\,X_2 - 0.00679\,X_3 + 0.1215502\,X_4 + 0.0189657\,X_5$$

- $\hat{y}$ = internal temperature of jig
- X_1= Temp
- X_2= Humidity
- X_3= Solar Radiation
- X_4= Wind Speed
- X_5= Wind Direction

J-5 Test 7 – A Model building and testing.

<u>Create a Linear Regression Model using stepwise with 80% of data randomly selected</u>

Summary of Fit

RSquare	0.91684
RSquare Adj	0.912553
Root Mean Square Error	2.488408
Mean of Response	66.96935
Observations (or Sum Wgts)	103

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	5	6622.0452	1324.41	213.8843
Error	97	600.6411	6.19	**Prob > F**
C. Total	102	7222.6863		<.0001*

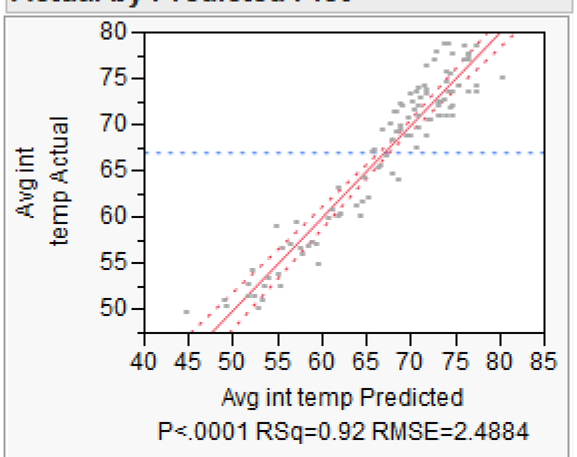
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|	Std Beta	VIF
Intercept	-3.865584	3.015655	-1.28	0.2030	0	.
PWS Temperature	1.1541796	0.043004	26.84	<.0001*	0.911606	1.3456993
PWS Humidity	-0.124578	0.018878	-6.60	<.0001*	-0.23864	1.5253325
PWS Solar Radiation	-0.018952	0.001769	-10.71	<.0001*	-0.43584	1.9304499
PWS Wind Speed	0.7746298	0.135415	5.72	<.0001*	0.179275	1.1456201
PWS Wind Direction	0.0191295	0.003113	6.15	<.0001*	0.199223	1.2256349

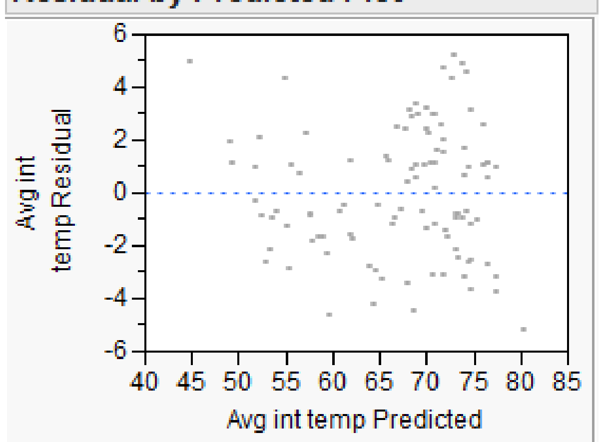
Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
PWS Temperature	1	1	4460.3120	720.3141	<.0001*
PWS Humidity	1	1	269.6539	43.5475	<.0001*
PWS Solar Radiation	1	1	710.7117	114.7758	<.0001*
PWS Wind Speed	1	1	202.6263	32.7229	<.0001*
PWS Wind Direction	1	1	233.8915	37.7721	<.0001*

Actual by Predicted Plot



Residual by Predicted Plot



Analysis of Variance (ANOVA) to test effects of chosen variables

Test 1: an overall F-test to see if there is an effect, $p<0.05$, one of the variables explains the variability

Ho: NONE of the factors explain variability

Ha: AT LEAST ONE of the factors explains variability

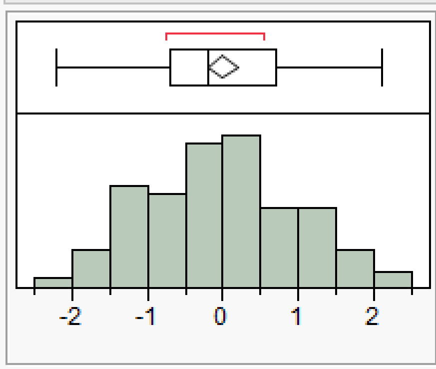
Test 2: Interaction Effect Test to see if combination of variables causes the effect. Ensure VIF score <5 to prevent multicollinearity (if VIF>5, one of the variables must be removed).

Test for Outliers

- Studentized Residuals Histogram Analysis

Distributions

Studentized Resid Avg int temp



Quantiles

100.0%	maximum	2.12303
99.5%		2.12303
97.5%		2.03414
90.0%		1.28525
75.0%	quartile	0.69781
50.0%	median	-0.1973
25.0%	quartile	-0.704
10.0%		-1.3142
2.5%		-1.8478
0.5%		-2.2068
0.0%	minimum	-2.2068

Summary Statistics

Mean	-0.00189
Std Dev	1.0047073
Std Err Mean	0.0989968
Upper 95% Mean	0.1944696
Lower 95% Mean	-0.19825
N	103
Range	4.3298475

If Normal:

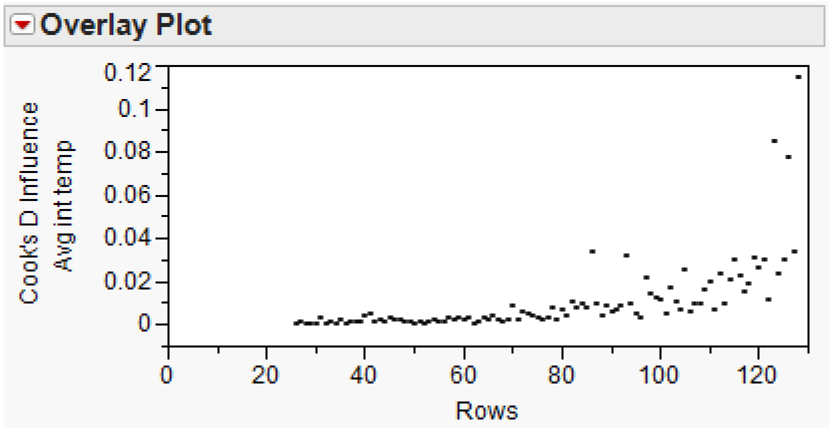
- 99.7% of normalized residuals should be within +/- 3 S.D.s

- 95% of normalized residuals should be within +/- 2 S.D.s

* Removed data point on 10/13/2015 at hour 7.5 as it was flagged as an outlier and overly influential

Test for Overly-Influential Data points

-Ensure no points are outside of 0.5



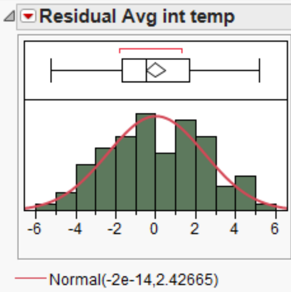
Test assumptions of the empirical rule

Test for Normality

Using Shapiro-Wilks test for goodness-of-fit

Distributions

Residual Avg int temp



Quantiles

100.0%	maximum	5.17386
99.5%		5.17386
97.5%		4.87715
90.0%		3.13427
75.0%	quartile	1.69333
50.0%	median	-0.4819
25.0%	quartile	-1.6845
10.0%		-3.2006
2.5%		-4.5198
0.5%		-5.2261
0.0%	minimum	-5.2261

Summary Statistics

Mean	-2.08e-14
Std Dev	2.4266517
Std Err Mean	0.2391051
Upper 95% Mean	0.4742638
Lower 95% Mean	-0.474264
N	103
Range	10.39993

Fitted Normal

Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Location	μ	-2.08e-14	-0.474264	0.4742638
Dispersion	σ	2.4266517	2.1344599	2.812263

-2log(Likelihood) = 473.922891005991

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.982059	0.1767

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Test for Constant Variance

Breusch-Pagan Test

Ho: Residuals have Constant Variance

Ha: Residuals do NOT have constant Variance

Breusch-Pagan Test

N	102
df(Exp)	5
SSE	600.6411
SSR	88.4776

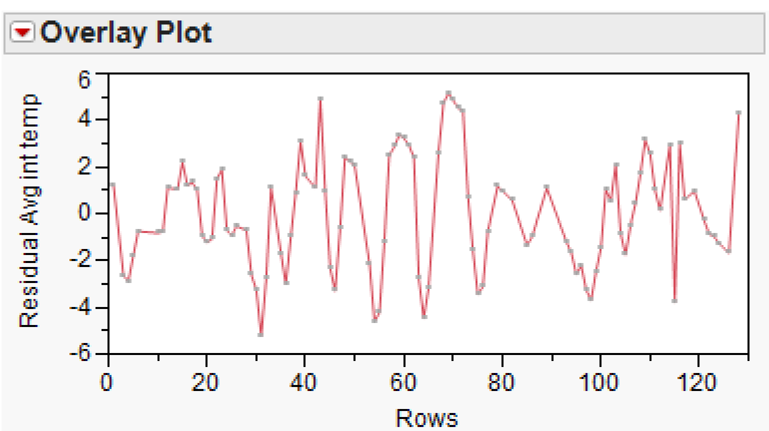
T.S.	**1.275774**
Pvalue	**0.937405**

Fail to reject the null hypothesis: residuals have constant variance

Testing for Independence

- Non-ordered data (observational) looking for trends over time. No Trends means residuals are independent over time

*Not all days shown, but representative of test period



- There is a trend in the data, therefore residuals fail for independence

Usefulness of Model

Mean Absolute Percent Error

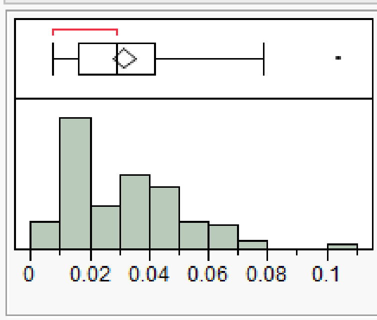
Absolute value of what the model observed (or actual), minus the predicted, all divided by observed

$$\frac{\left|y-\dot{y}\right|}{y}\times 100\%$$

Working Set (random 80% of data)

Distributions

Mean APE



Quantiles

100.0%	maximum	0.10385
99.5%		0.10385
97.5%		0.07357
90.0%		0.05934
75.0%	quartile	0.04195
50.0%	median	0.02923
25.0%	quartile	0.01593
10.0%		0.01049
2.5%		0.0076
0.5%		0.00729
0.0%	minimum	0.00729

Summary Statistics

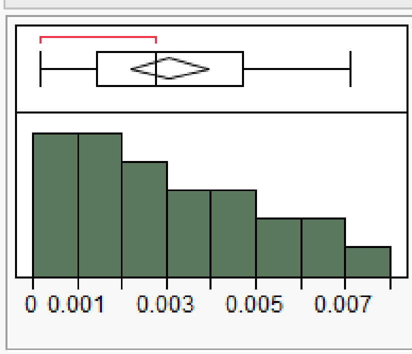
Mean	0.031511
Std Dev	0.0192092
Std Err Mean	0.0018927
Upper 95% Mean	0.0352652
Lower 95% Mean	0.0277568
N	103
Range	0.0965615

Mean = 0.032 shows a 3.2% error

Validation set (remaining 20% of data)

Distributions

Mean APE



Quantiles

100.0%	maximum	0.00714
99.5%		0.00714
97.5%		0.00714
90.0%		0.00642
75.0%	quartile	0.00468
50.0%	median	0.00274
25.0%	quartile	0.00143
10.0%		0.00023
2.5%		0.00014
0.5%		0.00014
0.0%	minimum	0.00014

Summary Statistics

Mean	0.0030481
Std Dev	0.0021004
Std Err Mean	0.0004201
Upper 95% Mean	0.0039151
Lower 95% Mean	0.0021811
N	25
Range	0.0070031

Mean = 0.003 shows a 0.3% error

Model Equation

$$\hat{y} = -3.865584 + 1.1541796\,X_1 - 0.124578\,X_2 - 0.018952\,X_3 + 0.7746298\,X_4 + 0.0191295\,X_5$$

- $\hat{y}$ = internal temperature of jig
- X_1= Temp
- X_2= Humidity
- X_3= Solar Radiation
- X_4= Wind Speed
- X_5= Wind Direction

J-6 Test 8 – A Model building and testing.

<u>Create a Linear Regression Model using stepwise with 80% of data randomly selected</u>

Summary of Fit

RSquare	0.908864
RSquare Adj	0.908089
Root Mean Square Error	3.249249
Mean of Response	58.7685
Observations (or Sum Wgts)	475

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	4	49485.001	12371.3	1171.784
Error	470	4962.081	10.6	Prob > F
C. Total	474	54447.082		<.0001*

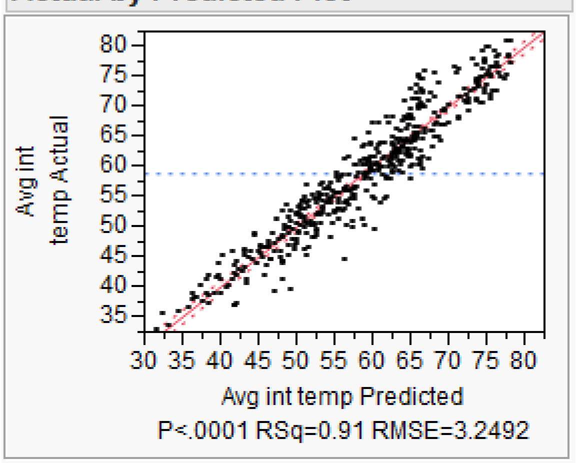
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|	Std Beta	VIF
Intercept	-5.968846	1.001722	-5.96	<.0001*	0	.
PWS Temperature	1.0578358	0.016042	65.94	<.0001*	0.926947	1.0190123
PWS Solar Radiation	-0.008782	0.000681	-12.90	<.0001*	-0.18718	1.0850239
PWS Wind Speed	0.3107836	0.048212	6.45	<.0001*	0.099032	1.2171503
PWS Wind Direction	0.0106558	0.001909	5.58	<.0001*	0.086172	1.2287424

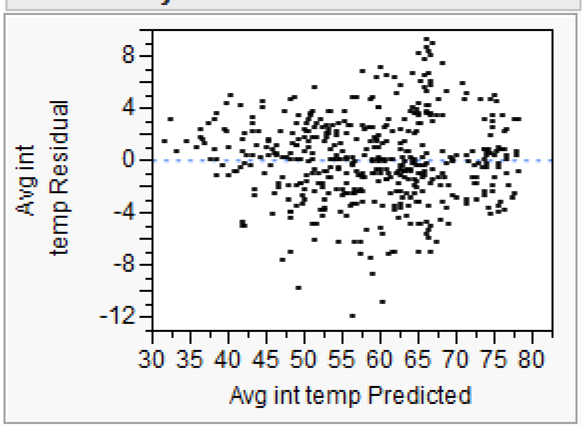
Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
PWS Temperature	1	1	45909.727	4348.492	<.0001*
PWS Solar Radiation	1	1	1758.090	166.5233	<.0001*
PWS Wind Speed	1	1	438.713	41.5541	<.0001*
PWS Wind Direction	1	1	329.036	31.1657	<.0001*

Actual by Predicted Plot



Residual by Predicted Plot



<u>Analysis of Variance (ANOVA) to test effects of chosen variables</u>

Test 1: an overall F-test to see if there is an effect, $p<0.05$, one of the variables explains the variability

Ho: NONE of the factors explain variability

Ha: AT LEAST ONE of the factors explains variability

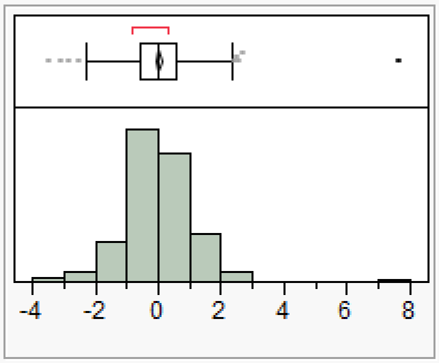
Test 2: Interaction Effect Test to see if combination of variables causes the effect. Ensure VIF score <5 to prevent multicollinearity (if VIF>5, one of the variables must be removed).

<u>Test for Outliers</u>

- Studentized Residuals Histogram Analysis

Distributions

Studentized Resid Avg int temp



Quantiles

100.0%	maximum	7.64911
99.5%		2.64261
97.5%		1.91661
90.0%		1.1782
75.0%	quartile	0.59172
50.0%	median	-0.0327
25.0%	quartile	-0.6051
10.0%		-1.1428
2.5%		-2.0202
0.5%		-3.0412
0.0%	minimum	-3.4902

Summary Statistics

Mean	0.0003978
Std Dev	1.0008419
Std Err Mean	0.0458735
Upper 95% Mean	0.0905379
Lower 95% Mean	-0.089742
N	476
Range	11.139325

*Excluded data point on 02/02/2016 at 7.5 hours as an outlier

If Normal:

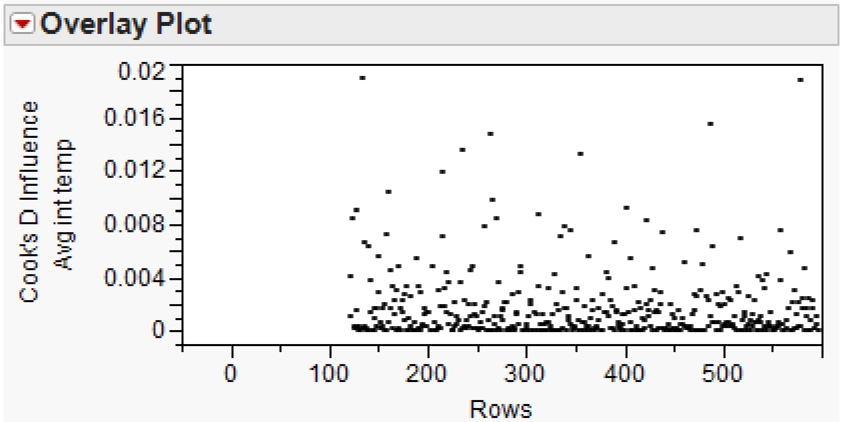
- 99.7% of normalized residuals should be within +/- 3 S.D.s

- 95% of normalized residuals should be within +/- 2 S.D.s

* Removed data point on 10/13/2015 at hour 7.5 as it was flagged as an outlier and overly influential

Test for Overly-Influential Data points

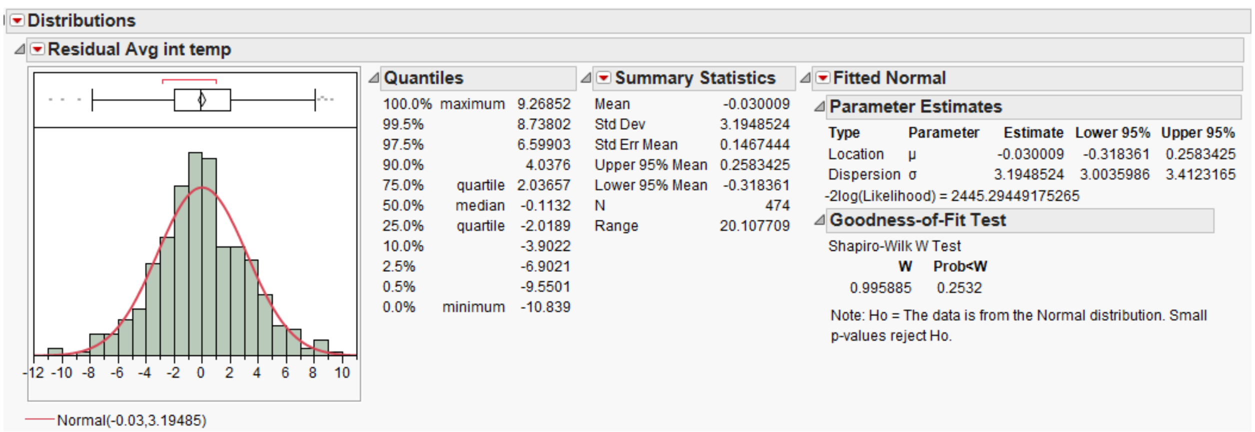
-Ensure no points are outside of 0.5



Test assumptions of the empirical rule

Test for Normality

Using Shapiro-Wilks test for goodness-of-fit



*Excluded data point on 01/25/2016 at 9.5 hours

Test for Constant Variance

Breusch-Pagan Test

Ho: Residuals have Constant Variance

Ha: Residuals do NOT have constant Variance

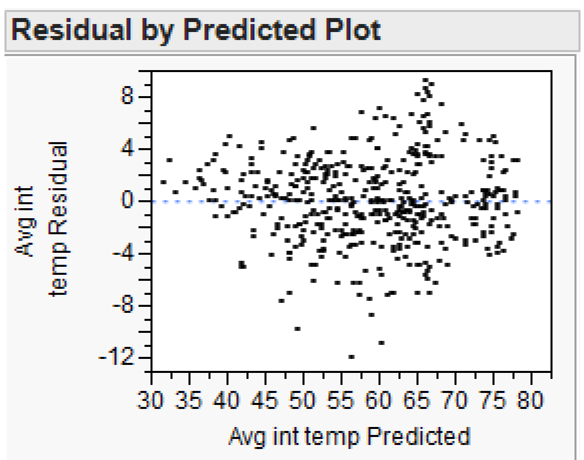
Breusch-Pagan Test

N	475
df(Exp)	4
SSE	4962.081
SSR	6755.84

T.S.	**30.95344**
Pvalue	**3.13E-06**

*Reject the null hypothesis: residuals DO NOT have constant variance

Visually inspect residual by predicted plot

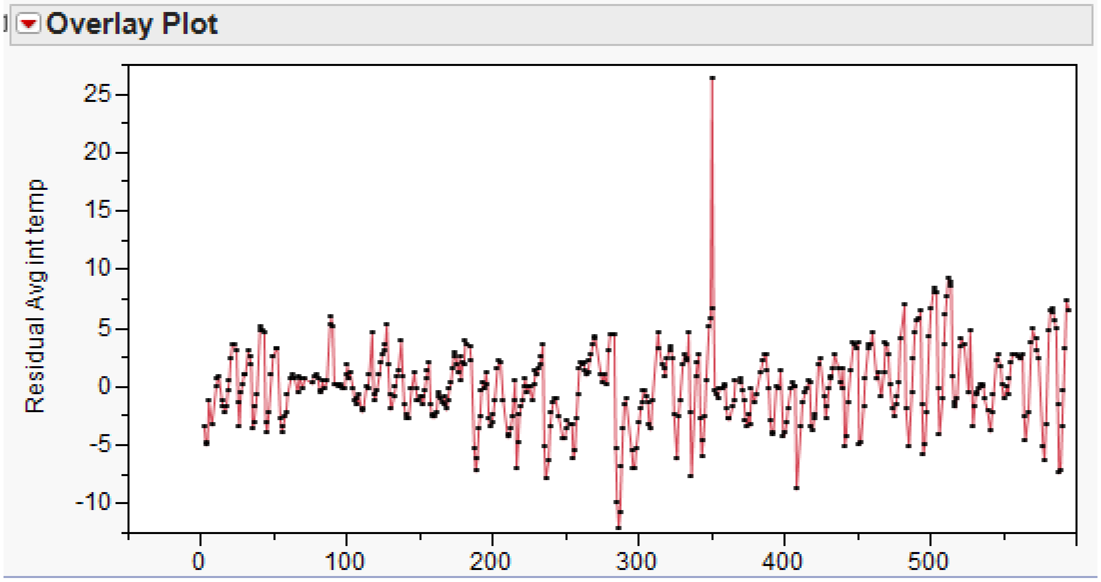


-See if it Vs out or in and compare the majority grouping top and bottom range to the extreme top and bottom range. If the extreme range is less than 2x the majority grouping range, this is a "Soft" Fail. Continue on.

Testing for Independence

- Non-ordered data (observational) looking for trends over time. No Trends means residuals are independent over time

*Not all days shown, but representative of test period



Usefulness of Model

Mean Absolute Percent Error

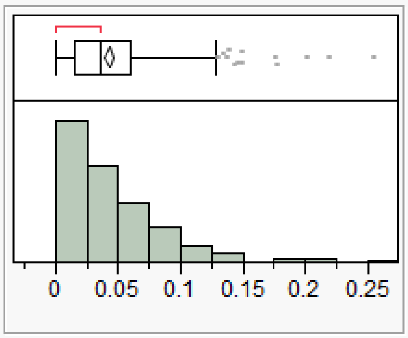
Absolute value of what the model observed (or actual), minus the predicted, all divided by observed

$$\frac{\left|y-\dot{y}\right|}{y}\times 100\%$$

Working Set (random 80% of data)

Distributions

Mean APE



Quantiles

100.0%	maximum	0.25384
99.5%		0.2126
97.5%		0.13483
90.0%		0.09124
75.0%	quartile	0.06034
50.0%	median	0.03624
25.0%	quartile	0.01468
10.0%		0.0046
2.5%		0.00102
0.5%		0.00015
0.0%	minimum	6.87e-6

Summary Statistics

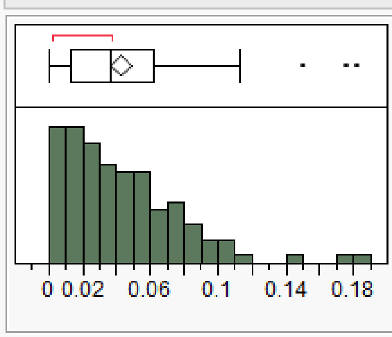
Mean	0.0428847
Std Dev	0.0368184
Std Err Mean	0.0016911
Upper 95% Mean	0.0462078
Lower 95% Mean	0.0395617
N	474
Range	0.2538359

Mean = 0.043 shows a 4.3% error

Validation set (remaining 20% of data)

Distributions

Mean APE



Quantiles

100.0%	maximum	0.18225
99.5%		0.18225
97.5%		0.14986
90.0%		0.08786
75.0%	quartile	0.06196
50.0%	median	0.03638
25.0%	quartile	0.01297
10.0%		0.0067
2.5%		0.00242
0.5%		0.00073
0.0%	minimum	0.00073

Summary Statistics

Mean	0.0428127
Std Dev	0.034894
Std Err Mean	0.0031987
Upper 95% Mean	0.049147
Lower 95% Mean	0.0364783
N	119
Range	0.1815264

Mean = 0.043 shows a 4.3% error

Model Equation

$$\hat{y} = -5.968846 + 1.0578358\, X_1 - 0.008782\, X_3 + 0.3107836\, X_4 + 0.0106558\, X_5$$

- $\hat{y}$ = internal temperature of jig
- X_1= Temp
- X_2= Humidity
- X_3= Solar Radiation
- X_4= Wind Speed
- X_5= Wind Direction

J-7 Test 9 – A Model building and testing.

Create a Linear Regression Model using stepwise with 80% of data randomly selected

Summary of Fit

RSquare	0.830177
RSquare Adj	0.818329
Root Mean Square Error	2.95588
Mean of Response	64.48593
Observations (or Sum Wgts)	47

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	3	1836.6034	612.201	70.0682
Error	43	375.7006	8.737	**Prob > F**
C. Total	46	2212.3041		<.0001*

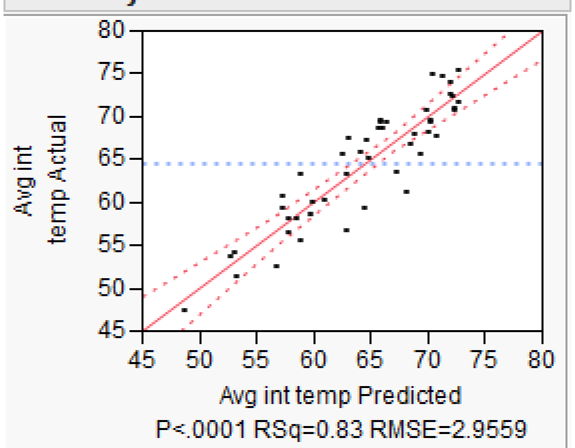
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|	Std Beta	VIF
Intercept	-12.42792	6.113891	-2.03	0.0483*	0	.
PWS Temperature	1.1590638	0.104905	11.05	<.0001*	0.828358	1.423267
PWS Solar Radiation	-0.007294	0.001918	-3.80	0.0004*	-0.27611	1.3345023
PWS Wind Speed	1.1082784	0.209279	5.30	<.0001*	0.359757	1.1685366

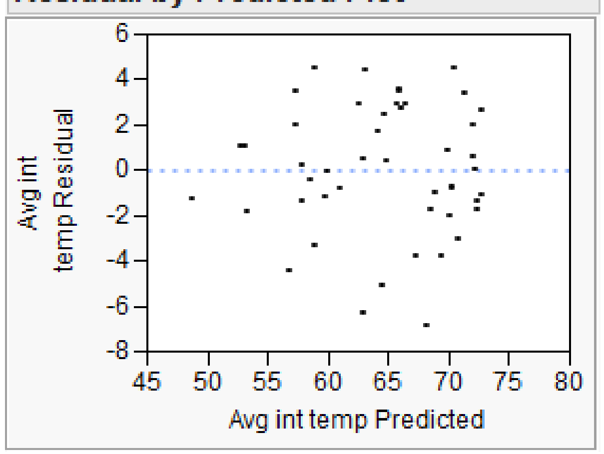
Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
PWS Temperature	1	1	1066.5835	122.0735	<.0001*
PWS Solar Radiation	1	1	126.3863	14.4653	0.0004*
PWS Wind Speed	1	1	245.0309	28.0445	<.0001*

Actual by Predicted Plot



Residual by Predicted Plot



Analysis of Variance (ANOVA) to test effects of chosen variables

Test 1: an overall F-test to see if there is an effect, $p<0.05$, one of the variables explains the variability

Ho: NONE of the factors explain variability

Ha: AT LEAST ONE of the factors explains variability

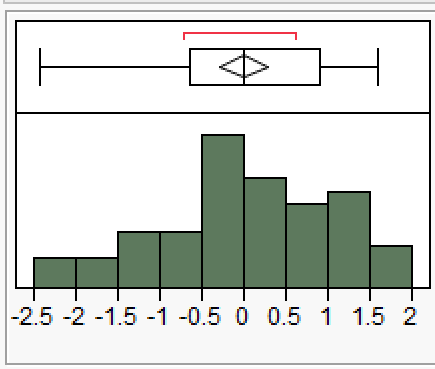
Test 2: Interaction Effect Test to see if combination of variables causes the effect. Ensure VIF score <5 to prevent multicollinearity (if VIF>5, one of the variables must be removed).

Test for Outliers

- Studentized Residuals Histogram Analysis

Distributions

Studentized Resid Avg int temp



Quantiles

100.0%	maximum	1.59988
99.5%		1.59988
97.5%		1.59653
90.0%		1.24778
75.0%	quartile	0.91289
50.0%	median	0.00359
25.0%	quartile	-0.6432
10.0%		-1.4084
2.5%		-2.3727
0.5%		-2.4288
0.0%	minimum	-2.4288

Summary Statistics

Mean	-0.000805
Std Dev	1.0055416
Std Err Mean	0.1466733
Upper 95% Mean	0.2944332
Lower 95% Mean	-0.296043
N	47
Range	4.0286833

*Excluded data point on 02/02/2016 at 7.5 hours as an outlier

If Normal:

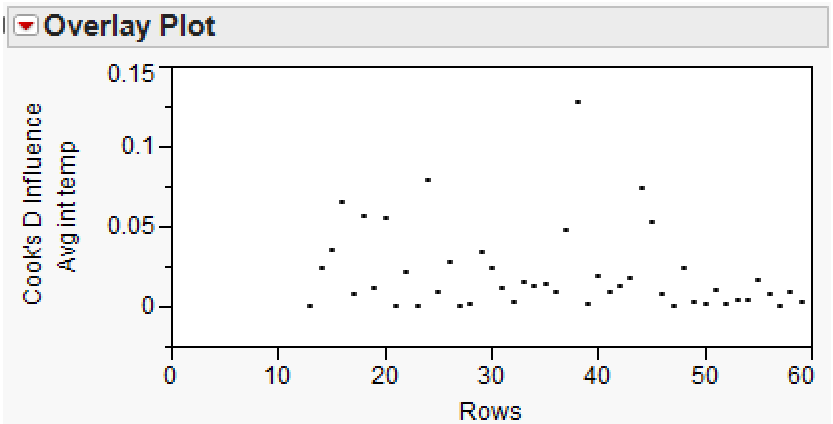
- 99.7% of normalized residuals should be within +/- 3 S.D.s

- 95% of normalized residuals should be within +/- 2 S.D.s

* Removed data point on 10/13/2015 at hour 7.5 as it was flagged as an outlier and overly influential

Test for Overly-Influential Data points

-Ensure no points are outside of 0.5



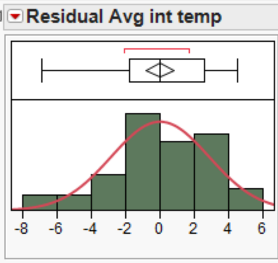
Test assumptions of the empirical rule

Test for Normality

Using Shapiro-Wilks test for goodness-of-fit

Distributions

Residual Avg int temp



Quantiles

100.0%	maximum	4.51225
99.5%		4.51225
97.5%		4.51075
90.0%		3.49533
75.0%	quartile	2.61755
50.0%	median	0.01006
25.0%	quartile	-1.7568
10.0%		-3.9622
2.5%		-6.766
0.5%		-6.8883
0.0%	minimum	-6.8883

Summary Statistics

Mean	-4.99e-15
Std Dev	2.8578672
Std Err Mean	0.4168628
Upper 95% Mean	0.8391012
Lower 95% Mean	-0.839101
N	47
Range	11.400584

Fitted Normal

Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Location	μ	-4.99e-15	-0.839101	0.8391012
Dispersion	σ	2.8578672	2.3748159	3.5894408

-2log(Likelihood) = 231.08732856609

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.967335	0.2092

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Test for Constant Variance

Breusch-Pagan Test

Ho: Residuals have Constant Variance

Ha: Residuals do NOT have constant Variance

Breusch-Pagan Test

N	47
df(Exp)	3
SSE	375.7006
SSR	133.5287

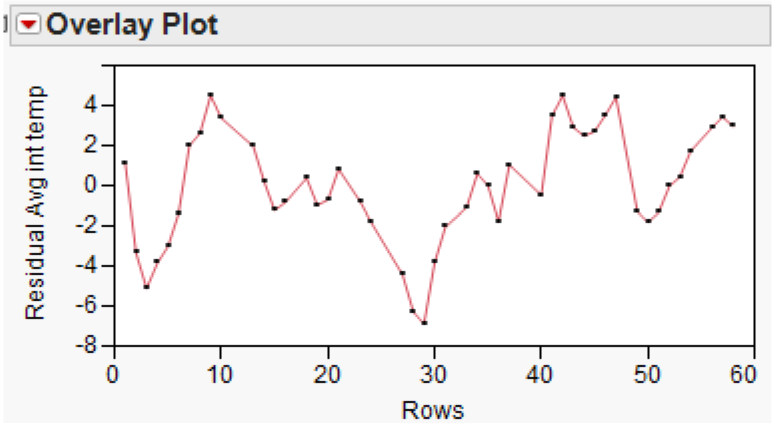
T.S.	**1.044856**
Pvalue	**0.7904**

Fail to reject the null hypothesis: residuals have constant variance

Testing for Independence

- Non-ordered data (observational) looking for trends over time. No Trends means residuals are independent over time

*Not all days shown, but representative of test period



Usefulness of Model

Mean Absolute Percent Error

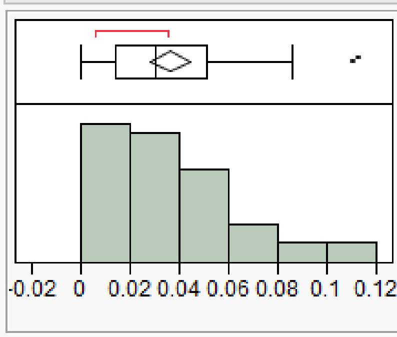
Absolute value of what the model observed (or actual), minus the predicted, all divided by observed

$$\frac{\left|y - \dot{y}\right|}{y} \times 100\%$$

Working Set (random 80% of data)

Distributions

Mean APE



Quantiles

100.0%	maximum	0.11255
99.5%		0.11255
97.5%		0.11223
90.0%		0.07383
75.0%	quartile	0.05083
50.0%	median	0.03012
25.0%	quartile	0.0143
10.0%		0.00684
2.5%		0.0002
0.5%		0.00014
0.0%	minimum	0.00014

Summary Statistics

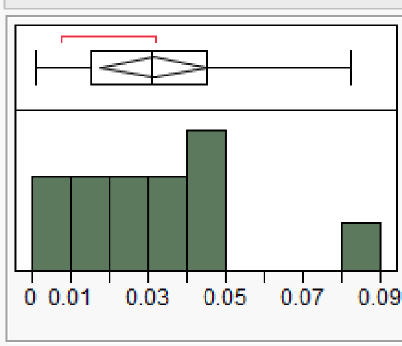
Mean	0.0362424
Std Dev	0.0270785
Std Err Mean	0.0039498
Upper 95% Mean	0.044193
Lower 95% Mean	0.0282918
N	47
Range	0.1124133

Mean = 0.036 shows a 3.6% error

Validation set (remaining 20% of data)

Distributions

Mean APE



Quantiles

100.0%	maximum	0.08247
99.5%		0.08247
97.5%		0.08247
90.0%		0.07215
75.0%	quartile	0.04516
50.0%	median	0.03068
25.0%	quartile	0.01512
10.0%		0.00298
2.5%		0.00096
0.5%		0.00096
0.0%	minimum	0.00096

Summary Statistics

Mean	0.0315317
Std Dev	0.0219286
Std Err Mean	0.0063302
Upper 95% Mean	0.0454645
Lower 95% Mean	0.017599
N	12
Range	0.0815066

Mean = 0.032 shows a 3.2% error

Model Equation

$$\hat{y} = -12.42792 + 1.1590638\,X_1 - 0.007294\,X_3 + 1.1082784\,X_4$$

- $\hat{y}$ = internal temperature of jig
- X_1= Temp
- X_2= Humidity
- X_3= Solar Radiation
- X_4= Wind Speed
- X_5= Wind Direction

J-8 Test 10 – A Model building and testing.

<u>Create a Linear Regression Model using stepwise with 80% of data randomly selected</u>

Summary of Fit

RSquare	0.887465
RSquare Adj	0.883806
Root Mean Square Error	2.744232
Mean of Response	74.25606
Observations (or Sum Wgts)	128

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	4	7304.8605	1826.22	242.4992
Error	123	926.2896	7.53	Prob > F
C. Total	127	8231.1501		<.0001*

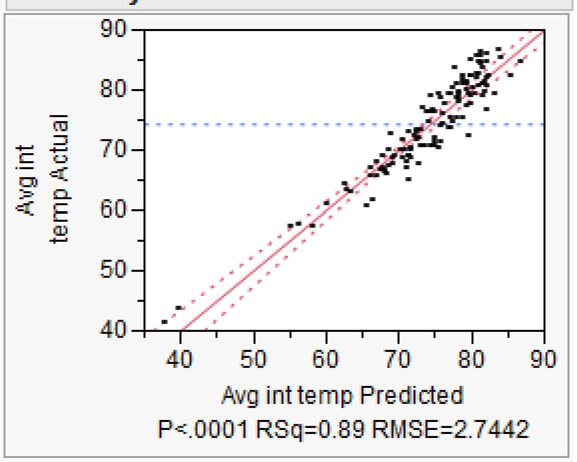
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|	Std Beta	VIF
Intercept	-19.1909	3.626764	-5.29	<.0001*	0	.
PWS Temperature	1.3011764	0.057662	22.57	<.0001*	0.839276	1.5119671
PWS Humidity	-0.049193	0.024434	-2.01	0.0463*	-0.08367	1.8879667
PWS Solar Radiation	0.0026807	0.001202	2.23	0.0275*	0.097892	2.1047053
PWS Wind Direction	0.017778	0.004393	4.05	<.0001*	0.137545	1.2627167

Effect Tests

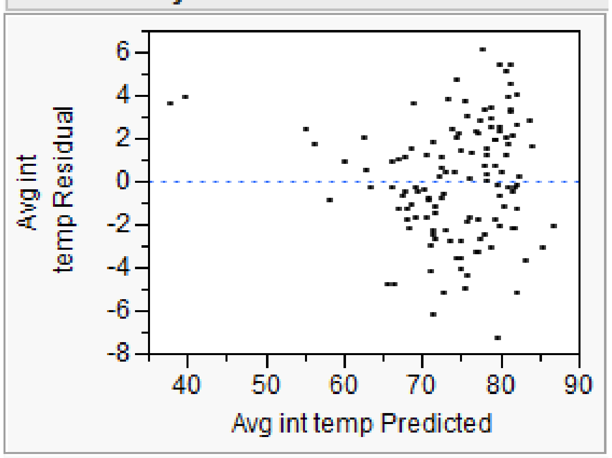
Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
PWS Temperature	1	1	3834.6706	509.1977	<.0001*
PWS Humidity	1	1	30.5250	4.0534	0.0463*
PWS Solar Radiation	1	1	37.4771	4.9765	0.0275*
PWS Wind Direction	1	1	123.3222	16.3757	<.0001*

Actual by Predicted Plot



P<.0001 RSq=0.89 RMSE=2.7442

Residual by Predicted Plot



Analysis of Variance (ANOVA) to test effects of chosen variables

Test 1: an overall F-test to see if there is an effect, $p<0.05$, one of the variables explains the variability

Ho: NONE of the factors explain variability

Ha: AT LEAST ONE of the factors explains variability

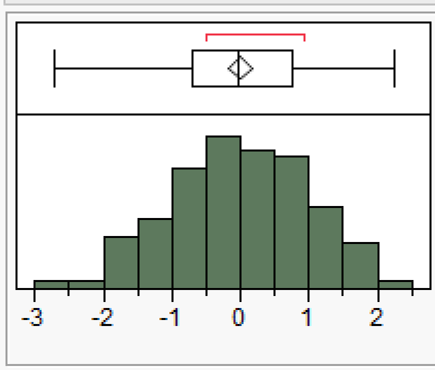
Test 2: Interaction Effect Test to see if combination of variables causes the effect. Ensure VIF score <5 to prevent multicollinearity (if VIF>5, one of the variables must be removed).

Test for Outliers

- Studentized Residuals Histogram Analysis

Distributions

Studentized Resid Avg int temp



Quantiles

100.0%	maximum	2.2364
99.5%		2.2364
97.5%		1.95845
90.0%		1.3649
75.0%	quartile	0.76314
50.0%	median	-0.0253
25.0%	quartile	-0.6973
10.0%		-1.3116
2.5%		-1.9154
0.5%		-2.7137
0.0%	minimum	-2.7137

Summary Statistics

Mean	0.003668
Std Dev	1.0036078
Std Err Mean	0.0887072
Upper 95% Mean	0.1792036
Lower 95% Mean	-0.171868
N	128
Range	4.9500993

*Excluded data point on 02/02/2016 at 7.5 hours as an outlier

If Normal:

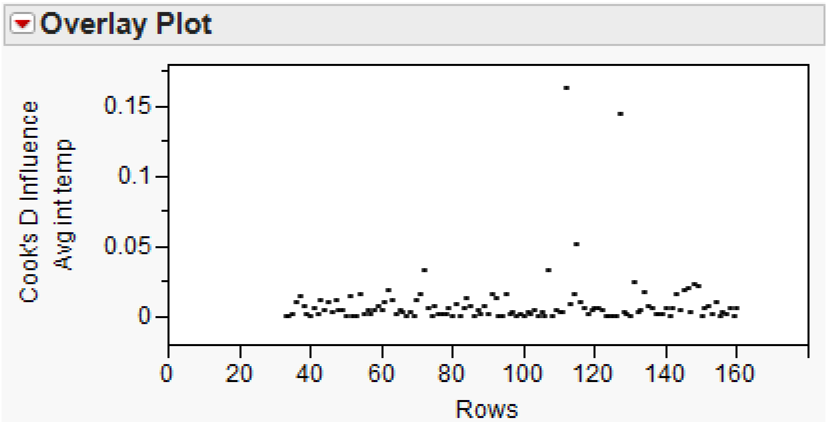
- 99.7% of normalized residuals should be within +/- 3 S.D.s

- 95% of normalized residuals should be within +/- 2 S.D.s

* Removed data point on 10/13/2015 at hour 7.5 as it was flagged as an outlier and overly influential

Test for Overly-Influential Data points

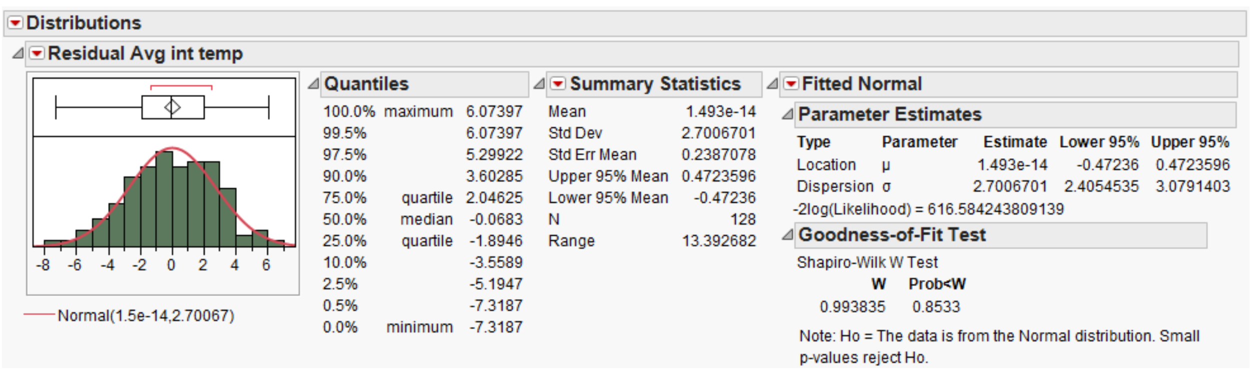
-Ensure no points are outside of 0.5



Test assumptions of the empirical rule

Test for Normality

Using Shapiro-Wilks test for goodness-of-fit



Distributions

Residual Avg int temp

Quantiles

100.0%	maximum	6.07397
99.5%		6.07397
97.5%		5.29922
90.0%		3.60285
75.0%	quartile	2.04625
50.0%	median	-0.0683
25.0%	quartile	-1.8946
10.0%		-3.5589
2.5%		-5.1947
0.5%		-7.3187
0.0%	minimum	-7.3187

Summary Statistics

Mean	1.493e-14
Std Dev	2.7006701
Std Err Mean	0.2387078
Upper 95% Mean	0.4723596
Lower 95% Mean	-0.47236
N	128
Range	13.392682

Fitted Normal

Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Location	μ	1.493e-14	-0.47236	0.4723596
Dispersion	σ	2.7006701	2.4054535	3.0791403

-2log(Likelihood) = 616.584243809139

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.993835	0.8533

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Test for Constant Variance

Breusch-Pagan Test

Ho: Residuals have Constant Variance

Ha: Residuals do NOT have constant Variance

Breusch-Pagan Test

N	128
df(Exp)	4
SSE	926.2896
SSR	764.165

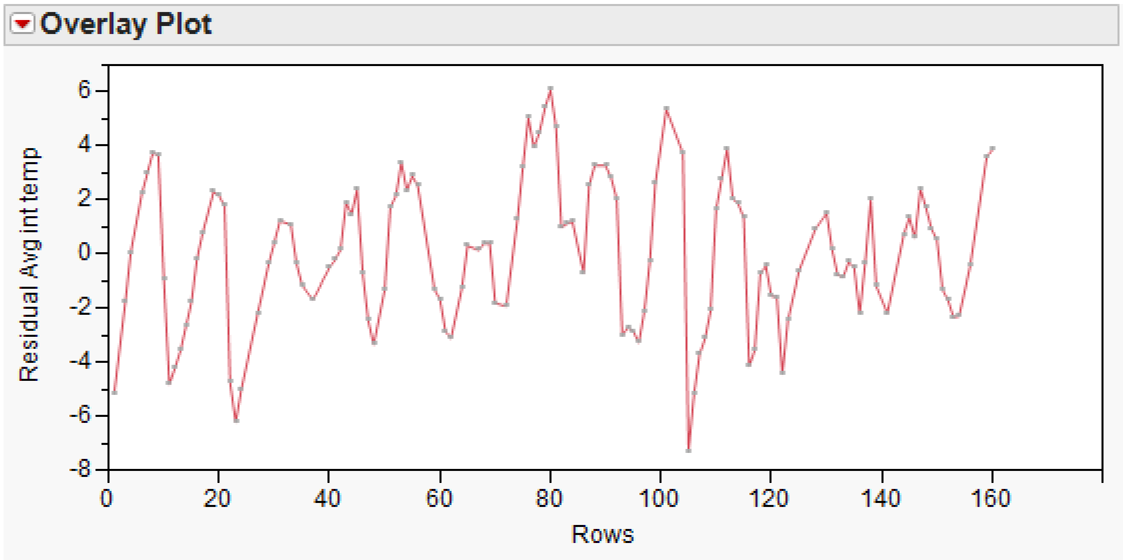
T.S.	**7.295978**
Pvalue	**0.12105**

Fail to reject the null hypothesis: residuals have constant variance

Testing for Independence

- Non-ordered data (observational) looking for trends over time. No Trends means residuals are independent over time

*Not all days shown, but representative of test period



Usefulness of Model

Mean Absolute Percent Error

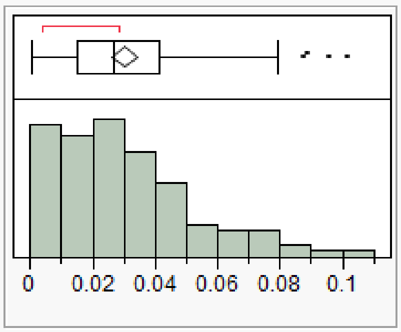
Absolute value of what the model observed (or actual), minus the predicted, all divided by observed

$$\frac{|y - \dot{y}|}{y} \times 100\%$$

Working Set (random 80% of data)

Distributions

Mean APE



Quantiles

100.0%	maximum	0.10131
99.5%		0.10131
97.5%		0.08813
90.0%		0.06226
75.0%	quartile	0.04101
50.0%	median	0.0264
25.0%	quartile	0.01494
10.0%		0.00523
2.5%		0.00208
0.5%		0.00059
0.0%	minimum	0.00059

Summary Statistics

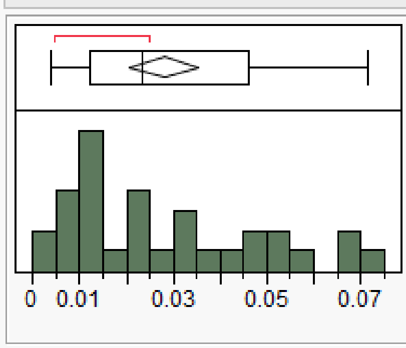
Mean	0.0302011
Std Dev	0.0218733
Std Err Mean	0.0019333
Upper 95% Mean	0.0340268
Lower 95% Mean	0.0263753
N	128
Range	0.1007173

Mean = 0.030 shows a 3.0% error

Validation set (remaining 20% of data)

Distributions

Mean APE



Quantiles

100.0%	maximum	0.07148
99.5%		0.07148
97.5%		0.07148
90.0%		0.06281
75.0%	quartile	0.04597
50.0%	median	0.02343
25.0%	quartile	0.01204
10.0%		0.00533
2.5%		0.00389
0.5%		0.00389
0.0%	minimum	0.00389

Summary Statistics

Mean	0.0279787
Std Dev	0.0201518
Std Err Mean	0.0035624
Upper 95% Mean	0.0352442
Lower 95% Mean	0.0207132
N	32
Range	0.0675912

Mean = 0.028 shows a 2.8% error

Model Equation

$$\hat{y} = -19.1909 + 1.3011764\, X_1 - 0.049193\, X_2 + 0.0026807\, X_3 + 0.0182042\, X_5$$

- $\hat{y}$ = internal temperature of jig
- X_1= Temp
- X_2= Humidity
- X_3= Solar Radiation
- X_4= Wind Speed
- X_5= Wind Direction

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Vita

Captain Justin E. Eshleman graduated from Hononegah Community High School in Rockton, Illinois. He studied at the Illinois Institute of Technology until May 2011, when he graduated with a Bachelor of Science in Civil Engineering and commissioned through AFROTC Detachment 195. After a year of inactive reserves, he was assigned to the 647th Civil Engineering Squadron at Joint Base Pearl Harbor-Hickam where he served as a construction manager for the Naval Facility Engineering Acquisition Division. During this time, he deployed to Al Udeid Air Base, Qatar where he worked with the Army Corps of Engineers on Military Construction (MILCON) projects as the Air Force Civil Engineer Center's (AFCEC) construction manager. He returned to Hawaii to work as an Airfield Assistant Public Works Officer. In August 2015, he was assigned to the Air Force Institute of Technology's Graduate School of Engineering and Management. In April 2017, he will join the 819th REDHORSE Squadron in Malmstrom AFB, Montana.

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The purpose of this research was to aid the Air Force Civil Engineer Center with the development, testing, and analysis of Advanced Energy Efficient Shelter Systems—ultimately leading to the procurement of next-generation shelter systems. Specifically, this research focused on the thermal performance of radiant barrier technology integrated into different types and configurations of fabric materials used for the fly, skin, and liner of temporary fabric shelter. The absence of testing standards specific to the thermal performance of temporary fabric shelters required testing procedures and thermal performance metrics to be analyzed and established. Then, a design of experiments was conducted using a modified hot box apparatus and small-scale test jigs resulting in over 57,350,000 data points capturing exterior climatic conditions and resulting temperatures of the materials and interior space. Comparisons of means and correlations were used to identify the optimal number of layers, number of radiant barriers, and placement and direction of radiant barriers. As a result, hot box air conditioning runtimes were reduced up to 54.6% compared to standard single layer systems while test jig interior temperatures decreased as much as 14.8°F. Finally, multiple regression

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