

## **ABSTRACT**

CANNON, FORREST R. Development and Validation of Bench-Level and Manikin Test Methods to Predict Heat Related Comfort Properties of Mattresses. (Under the direction of Dr. Emiel Den Hartog).

Mattresses are being developed and advanced to increase the thermal comfort of their users to increase sleep quality. However, there is no current standardized test method for assessing the thermal comfort of mattresses and cushioned materials. This research will seek to establish new testing methodologies for evaluating thermal properties of mattresses related to comfort by use of an inverted guarded hotplate and a segmented thermal manikin. These test devices and the described test methods were capable of producing repeatable results that described the thermal comfort of three mattresses in both the short term (<30 minutes) and long term (> 30 minutes). These test methods were validated by human comfort trials where 12 test subjects laid on the same three mattresses providing both objective and subjective information which were found to have similar data trends in thermal sensation as predicted by the test devices. The knowledge from this research will be useful to develop new material combinations and constructions of mattresses to offer different levels of insulation to optimize thermal comfort.

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Development and Validation of Bench-Level and Manikin Test Methods to Predict Heat  
Related Comfort Properties of Mattresses

by  
Forrest Cannon

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**DEDICATION**

This is dedicated to my family, friends, and professors who have inspired me along my way to grow as both a student and person. Thank you.

## **BIOGRAPHY**

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## **ACKNOWLEDGMENTS**

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## **CHAPTER 1: Introduction**

### **1.1 Purpose**

The effect that a mattress can have on sleep quality has been debated by researchers. Many of these research studies regarding mattresses were focused on their mechanical properties and their ability to affect the posture and, in turn, sleep quality and comfort of the user. Research has suggested that the mattress and bedding materials can sometimes be a contributing factor to the sleep quality and comfort of the user.

The effects of temperature on sleep quality and onset has also been studied. Skin temperature can also impact the amount of slow wave sleep and sleep maintenance (ability to stay asleep) of humans. The skin temperature of people is found to be influenced by posture, ambient temperature, environmental light, nutrition, bedding materials, and other factors [1]. Here, we will focus on the how bedding materials can provide different levels of insulation and impact the thermal comfort of users.

### **1.2 Test Methods**

Test methods already exist for assessing the durability and mechanical properties of mattresses. However, there are no current standardized methods for assessing thermal comfort of mattresses. Previous experiments have shown that bench top tests and thermal manikins have been used to determine thermal properties of cushioned materials such as seats and mattresses. However, this research is novel in relating the test results of two test devices to the results of a human protocol on the same mattresses. The purpose of this thesis

research was to create test methods for assessing the thermal properties of mattresses that are related to comfort using a thermal seat tester and thermal manikin and then validate these test methods through human comfort trials on three mattresses.

All of the following experiments took place in a controlled environmental chamber with conditions close to what would be expected in a standard home. An innerspring, foam, and foam with phase change materials (PCMs) were used throughout the research. The bench top test device resembled an inverted thermally guarded hot plate and the thermal manikin was segmented. For both of the test methods, the devices were set to maintain a constant surface temperature of 35°C during the experiments. Test device surface temperature, thermal resistance, and heat flux generated were among the variables used to characterize the thermal properties of the mattresses related to comfort. One-way ANOVA and repeated measures ANOVA tests were used to prove the statistical significance of these experiments performed.

## **CHAPTER 2: The Assessment of Thermal Comfort**

### **2.1 Introduction**

The purpose of this chapter is to summarize various approaches of assessing thermal comfort, particularly on mattresses and cushioned materials. There are a great number of physical values that affect the mattress comfort during sleep. Among them, thermal comfort is a critical and complicated aspect in the mattress evaluation.

Thermal comfort is “the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation” [2]. Thermal comfort greatly relies on heat balance. Heat balance occurs when the amount of heat an object gains equals the amount of heat that leaves the object. Human heat balance is essential to maintain a relatively constant core body temperature, which can be achieved by matching the rate of heat production and heat loss via physiological control. For thermal equilibrium to be achieved, the net heat flow must be from the body to the environment to account for the metabolic heat production. Heat loss depends on a temperature gradient from the body to the environment for dry heat loss via conduction, convection, and radiation, or a water vapor pressure gradient from the body to the environment for evaporative heat loss [3]. Equation 1 presented below can demonstrate the relationships.

$$\text{Eq. 1: } S = M - W_{\text{ext}} \pm C \pm K \pm R - E \pm \text{Resp},$$

Where  $S$  = heat storage,  $M$  = metabolism rate,  $W_{\text{ext}}$  = external work done by muscles,  $C$  = convection,  $K$  = conduction,  $R$  = radiation,  $E$  = evaporation,  $\text{Resp}$  = respiratory loss [3].

By analyzing the terms in the equation, the thermal comfort of human subjects is evaluated. It should be noted that for mattress evaluation, the environmental variables including temperature, relative humidity, and airflow should be kept constant.

The comfort in the case of sleep is based on a low metabolic equivalent. According to a study of heat production during sleeping, the metabolic equivalent  $M$  varies with sleeping

time due to different states of sleeps.  $M$  ranged from 68 to 75 W [4]. The metabolic equivalent  $M$  of the first hour of sleep and the last hour before awake were shown to be much higher, which makes them not suitable for the present study. For the rest of time, the average metabolic equivalent is 70W, which is adapted by sleep comfort studies such as Cheng's [5]. Bischoff and colleagues reported a close metabolism rate of  $40\text{W}/\text{m}^2$  or 0.7 met [6]. This metabolic rate is more widely accepted by sleep scientists [7]–[10]. The heat transfer between the human body and the environment on a mattress with a covering according to Leung is presented in Figure 1 below.

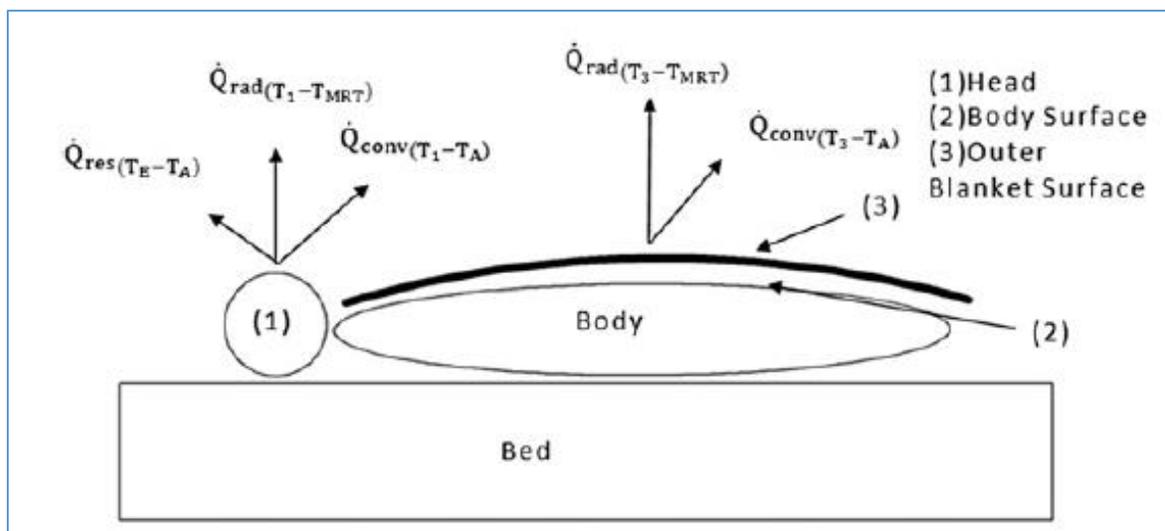
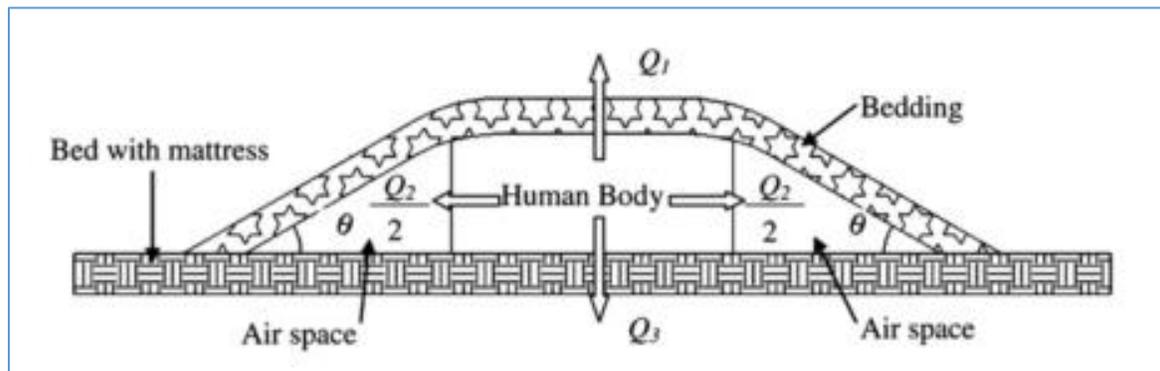


Figure 1 – Human Heat Transfer on Mattress [10]

A problem with this diagram of body heat transfer is that it does not account for the heat that is lost through the back of the head and the body through the mattress which is of much interest for the present study [10]. Pan, Lin, and Deng recognize, however, that a sleeping human in a bedding system transfers heat in four main ways –  $Q_1$  heat flow through

bedding or sheets in contact with the skin,  $Q_2$  heat flow to air pockets under the bedding system created by drape of the bedding over the sleeping subject,  $Q_3$  heat flow through the mattress which the subject is laying on, and  $Q_4$  heat flow through the skin which is not under the bedding to the ambient room environment (typically the head of a sleeping person).

Their schematic of heat transfer of a sleeping human subject in a bedding system, shown below in Figure 2, conveys the heat flow to these first three areas, but does not show the heat flow from the areas of the body that are not covered. This schematic was simplified for the calculation of total insulation value of a bedding system (discussed later) and assumes that the shape of a human is a rectangle while the shape of the bedding/sheets is a trapezoid [11].



*Figure 2 – Cross Section of Human Heat Transfer in a Bedding System [11]*

A study on the heat transfer by conductive warming with a circulating-water mattress demonstrated that there is much more heat transfer from the back than the legs of a human subject. The heat transfer was calculated by multiplying the heat flux per area by the area of contact with the mattress. The heat transfer from the back to the mattress was  $45.6 \pm 4.5$   $W/m^2$  and heat transfer from the legs to the mattress was  $24.7 \pm 4.3$   $W/m^2$  [12].

## **2.2 Mathematical models**

There are several mathematical models that establish the human body comfort in different aspects.

### ***2.2.1 Human thermal physiological models***

Heat transfer is a complicated process which involves lots of physical variables. To simplify the analysis, human thermal physiological models are established. The human thermal physiological models divide body parts into different nodes. Table 1 presents some typical models widely adapted.

*Table 1 – List of Human Thermal Physiological Models*

Model Name	Author & Date	Description
One-node	(Givoni & Goldman, 1971) [13]	Empirical, only applicable to hot environment
Two-node	(Gagge, Stolwijk, & Nishi, 1971) [14]	Core layer and skin surface layer are the two nodes, applicable to moderate activity levels and uniform environment conditions, limited to human exposure times of less than 1hr, cannot account for spatial non-uniformities
Multi-node (six-segment)	(Stolwijk, 1970)[15]	Constant environment conditions
UC Berkeley Comfort Model	(Tanabe, Tsuzuki, Kimura, & Horikawa, 2001) [15]	Originated from multi-node model, sixty-five segments, present heat and moisture capacitances, used in steady-state, transient environment
Comfort Equation for Sleeping Environments	[16]	Combines both environmental and personal variables to produce a thermoneutral sensation

### **2.2.2 Two-Node Model**

Two-node model by Gagge has been widely used in the analysis of predicting thermal

comfort in an indoor environment with the ability to model sweating. The model represents the basic thermo-regulatory processes in human body, which is the transport of metabolically generated heat and water vapor from the body to the surrounding air in the room [14].

The human skin and the body core (everything except skin) are designated as nodes 2 and 1.  $T_{sk}$  and  $T_{cr}$  designate body skin and core temperatures respectively. The core temperature is governed by metabolic heat generation, heat conduction, respiration and blood flow response to metabolic heat generation. The skin temperature is governed by radiation and convection of heat, evaporation of sweat and sensible heat arriving at skin through conduction in the core (skin blood flow).

The governing equations for energy transport of two-node model are expressed as [14]:

$$\text{Eq. 2: } S_{cr} = (M - Q_{res}) - K(T_{cr} - T_{sk}) - c_{p,bl} m_{bl}(T_{cr} - T_{sk})$$

$$\text{Eq. 3: } S_{sk} = K(T_{cr} - T_{sk}) + C_{p,bl} m_{bl} (T_c - T_{sk}) - E_{sk} - (Q_{cv} - Q_r)$$

In Equation 2,  $S_{cr}$  and  $S_{sk}$  are the sensible heat storage terms, which equals zero in this model.  $Q_{res}$  is the heat released due the body's respiration.  $K(T_{cr} - T_{sk})$  represents the sensible heat transfer from the core to the skin, where  $K$  is effective conductance between the core node and the skin layer ( $W/(m^2K)$ ).  $c_{p,bl} m_{bl}(T_{cr} - T_{sk})$  represents the heat transfer from the core to skin due to blood flow, where  $c_{p,bl}$  is specific heat of blood,  $4.187 \text{ kJ}/(\text{kg K})$ .

In conclusion, two-node model deals with whole body heat balance rather than localized heat balance. It is applicable for the conditions of moderate activity levels and uniform environment conditions [14]. However, two-node model is not the best approach for studies of mattress comfort, since it cannot describe the difference of skin temperature of

different body parts which could be impacted differently on the mattress.

### 2.2.3 Multi-node model

Multi-node model by Stolwijk (1970) was originally adapted in the application of aerospace environment. The Stolwijk model is comprised of six segments: the head, trunk, arms, hands, legs, and feet. Each of these segments is divided into four layers: the core, muscle, fat, and skin [15]. In addition, this model has a central blood compartment that is thermally connected to all the other nodes as Figure 3 demonstrates.

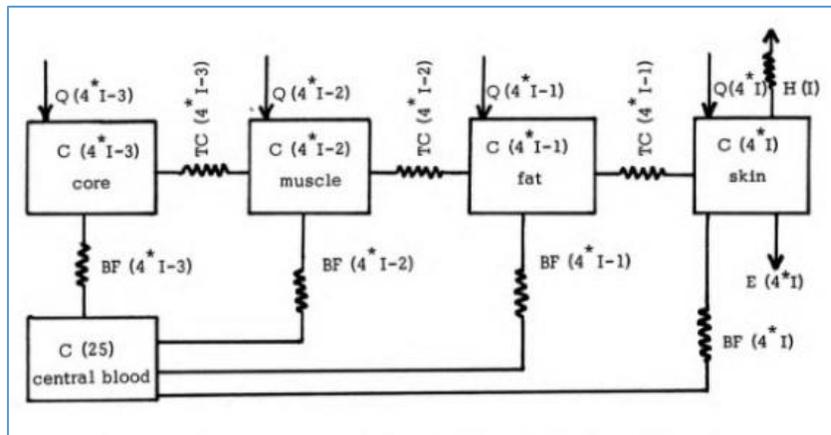


Figure 3 – Schematic Diagram of Layers of One Segment (Stolwijk, 1970)

The heat balance equation for each node is expressed as:

$$\text{Eq 4: } C(i, 1) \frac{dT(i, 1)}{dt} = Q(i, 1) - BC(i, 1) - TD(i, 1) - E(i, 1)$$

$$\text{Eq 5: } C(i, 2) \frac{dT(i, 2)}{dt} = Q(i, 2) - BC(i, 2) + TD(i, 2) - E(i, 2)$$

$$Eq\ 6: C(i, 3) \frac{dT(i, 3)}{dt} = Q(i, 3) - BC(i, 3) + TD(i, 3) - E(i, 3)$$

$$Eq\ 7: C(i, 4) \frac{dT(i, 4)}{dt} = Q(i, 4) - BC(i, 4) + TD(i, 4) - E(i, 4) - Q_t(i, 4)$$

And the heat balance equation for the central blood compartment is

$$Eq\ 8: C_{CB} \frac{dT_{CB}}{dt} = \sum_{i=1}^6 \sum_{j=1}^4 BC(i, j)$$

where  $i$  refers to the six segments and  $j$  refers to the four layers in the model,

$C(i, j)$  = thermal capacitance of the node (J/K),

$Q(i, j)$  = rate of heat production (W),

$BC(i, j)$  = convective heat transfer from node  $(i, j)$  to central blood (W),

$TD(i, j)$  = conductive heat transfer from layer  $j$  to layer  $j + 1$  (W),

$E(i, 4)$  = evaporative heat loss from the skin surface (W),

$Q_t(i, 4)$  = convective and radiative heat exchange rate between skin surface and environment (W),

and  $C_{CB}$  = thermal capacitance of blood (J/K).

This model can describe localized thermal comfort unlike the two-node model. While it is helpful to understand the concepts used by this model and that work has been done in creating mathematical models for thermal comfort, it is not necessary for the development of a test method for assessing the thermal comfort of mattresses.

#### ***2.2.4 Human Thermal Psychological Models***

Thermal psychological models are essential when carrying out a human subject study since psychological variables can affect the thermal sensation. People's subjective responses can be different even in the same thermal environment. Thermal psychological models are capable of predicting people's thermal sensation of different environment in different aspects.

There are a variety of psychological models to meet the needs of different applications. In general, the models can be classified according to different environmental conditions, that are steady-state, dynamic, uniform, non-uniform thermal environment. They can also be classified in terms of time, which are transient, usually less than one hour [17] and long-term thermal sensations. Most of the models originated from the classic Fanger's PMV-PPD model.

#### ***2.2.5 Fanger's PMV-PPD Model-Psychological Model***

Fanger's PMV-PPD model [18] is widely used and accepted for design and field assessment of thermal comfort. The empirical comfort equation was developed to map the regions of thermal comfort and discomfort by the indices Predicted Mean Vote (PMV) and Percentage of People Dissatisfied (PPD). The PMV index can predict the mean response of a large group of people. The result can be highly correlated with the ASHRAE thermal sensation scale [2]. PMV and PPD can be applicable on different fields according to Standard ISO 7730.

PMV index demonstrates the imbalance between the actual heat flow from a human body in a given environment and the heat flow required for optimum comfort at a specified activity by the following equation:

$$Eq\ 8: PMV = [0.303 \exp(-0.036M) + 0.028]L = \alpha L,$$

Where L is the thermal load on the body, defined as the difference between internal heat production and heat loss to the environment for a person to keep comfortable. A lower value of PMV value can stand for the feeling of satisfaction. PMV index has a high accuracy to correspond people's feeling. However, even with  $PMV = 0$ , about 5% of the people are dissatisfied [19].

This PMV equation presented by Fanger is not adequate to assess the thermal comfort in a sleeping environment, such as would be experienced on a mattress. One of the issues addressed with this equation is that the sensitivity coefficient,  $\alpha$ , is nearly impossible to validate in a very low activity study with a large number of human subjects. This sensitivity coefficient from his experiments did not account for the low activity levels achieved during rest. However, when extrapolation is applied to extend the range of metabolic rate down to  $40\text{ W/m}^2$  (0.7 met during sleep), the PMV for a sleeping environment can be calculated by the equation shown below [16].

$$Eq\ 9: PMV = 0.0998 \left\{ 40 - \frac{1}{R_t} \left[ \left( 34.6 - \frac{4.7\bar{t}_r + h_c t_a}{4.7 + h_c} \right) + 0.3762(5.52 - p_a) \right] \right\} \\ - 0.0998 [0.056(34 - t_a) + 0.692(5.87 - p_a)]$$

[16]

Where  $R_t$  = total resistance of a bedding system including the air layer around a covered body,  $\bar{t}_r$  = mean radiant temperature,  $h_c$  = convective heat transfer coefficient at surface,  $t_a$  = ambient air temperature, and  $p_a$  = water vapor pressure in ambient air (kPa).

PPD index with a given condition can also be estimated by the equation below.

$$Eq\ 10: PPD = 100 - 95 \exp[-(0.03353PMV^4 + 0.2179PMV^2)],$$

Here, dissatisfaction is defined as anybody not voting -1, +1, or 0.

Fanger's model combines the theories of heat balance with the physiology of thermoregulation to determine a range of comfort temperatures which people will find comfortable.

Lin and Deng's comfort equation for sleeping environments was designed to fulfill the three conditions required for thermal comfort. The first condition is that the heat balance equation needs to be satisfied, the second condition is the mean skin temperature required for comfort ( $^{\circ}C$ ), and the third condition is the evaporative heat loss due to regulatory sweating required for comfort ( $W/m^2$ ). The second and third conditions were proposed by Fanger. Fanger's modified PMV equation above was derived using the conditions for Lin and Deng's comfort equation for sleeping environments shown below [16].

$$Eq\ 11: 40 = \frac{1}{R_t} \left[ \left( 34.6 - \frac{4.7\bar{t}_r + h_c t_a}{4.7 + h_c} \right) + 0.3762(5.52 - p_a) \right] + 0.056(34 - t_a) + 0.692(5.87 - p_a)]$$

[16]

The PMV and PPD indexes by Fanger have been widely used in thermal comfort studies. While it is important to understand the factors and models that have been used in the

past for thermal comfort, these models were not used in the present mattress study because it is outside the scope of this project.

### **2.3 Methods for Assessing Thermal Comfort**

Although the purpose of the present study is to evaluate the mattress comfort, when carrying out an experiment, a complete bedding system (includes a blanket, bed sheet, pillow, and a mattress) should be used. This is because this setting is closer to the usage of average customers. However, the focus of this research is to be on the comfort properties most associated with the mattress. The analysis of mattresses should be controlled by having the rest of components in the bedding systems constant, and the environment for sleeping experiment contain steady-state humidity, temperature, and, if present, airflow.

#### ***2.3.1 Subjective methods: Standard, Questionnaire***

Subjective questionnaires are a straightforward method to obtain the direct response from participants. While subjective evaluations can provide useful data for the evaluation of thermal comfort, it is important to note that there are many complex factors which can influence a subjective response of a human. Some of the psycho-physiological factors, which can influence a subjective response, are the person's state of being, the style of the mattress, how it fits, and the familiarity to the mattress. Other stored modifiers held by the subjects could play equal influence on a subjective response such as past experiences, bias,

expectation, imaging (how they first judge the mattress based on appearance), and lifestyle of the test subjects [20].

There are several standards about thermal and comfort perception that can be helpful to this study. There are also different psychometric tools which can be used to obtain subjective information from test subjects. Likert scales/items, visual analog scales (VAS), and true/false subjective evaluation methods would be the most applicable tools used in obtaining information for the present study. A Likert item is a statement given to a respondent where the respondent must answer according to their level of agreement/disagreement with the given statement. The level of agreement is chosen from a group of about 2-13 possible answerers. For example, a common Likert item is the 5-point scale where the possible answers are -2 (strongly disagree), -1 (disagree), 0 (neither agree nor disagree / neutral), +1 (agree), +2 (strongly agree). These possible answers are equal in distance or magnitude from each other, such that options -2 and -1 are the same distance as options 0 and +1 [21]. Likert items can include or omit the 'neutral' option if it is desired to get a definite answer from the respondent [22]. If there are multiple statements for the test subject to answer, these answers can be summed together to form a Likert scale. The optimal number of possibilities of response is situation-based and empirical [23]. 5-9 point systems are considered the most practical because less than 5 options might make the differences between answer choices too extreme when the perceived difference of the subject is not that large, whereas the respondent might not have a strong enough sensitivity to accurately differentiate by adjacent levels of response [22].

Two most popular standards for subjective thermal sensation which use categorical scaling, such as the Likert method, are ISO 10551 and ASHRAE Standard 55. ISO 10551 [24] is a standard method of assessing of the influence of the thermal environment using subjective judgment scales. To evaluate the temperature sensation, subjects are required to rank the thermal comfort using a scale ranging from -4 (very cold) to +4 (very hot) and the comfort scale ranging from 0 (comfortable) to +4 (extremely uncomfortable). ASHRAE Standard 55 – 2004 contains the ASHRAE Thermal Sensation Scale which is on a 7 point scale from -3 (cold) to +3 (hot) with 0 being comfortable [2]. The Army Natick Laboratories use the 13-point McGinnis categorical scale [25]. The possible responses or options provided to the test subjects are more explanatory than those of the ISO/ASHRAE scales. The 13-point Taylor categorical scale requires subjects to provide a number to represent their whole body temperature based on the options provided [25].

VASs are also a common tool used to obtain subjective information from test subjects. A VAS is similar to the Likert scale because it provides a statement to a test subject and the subject is then intended to determine their level of agreement with the given statement. The main difference between the VAS and the Likert scale is the response method of the test subject. Instead of presenting a given number of responses and allowing the respondent to choose one of the options like the Likert method, VASs provide a straight line with two anchored end points (typically “Completely Disagree” and “Completely Agree”) and the respondent marks his/her feelings towards the statement. While there can be unipolar VASs which go from ‘none’ to ‘maximal’, thermal sensation is bi-dimensional which means

that the end points would be the extreme hot/cold sensations and the middle point of the line would be the equivalent of ‘neither cold nor hot’ [25]. The range of a VAS typically goes from 0-10 or 0-100. A bipolar numeric VAS ranges from 0-10 provides a middle point of 5. These numbers either be given to or hidden from the respondents, but the number is used for statistical evaluation of responses. It is common for categorical scales to be accompanied with VAS scales as with the ISO 10551 Standard, these are known as graphic categorical scales. Examples of these scales and other scales which have been used studies related to subjective thermal sensation are shown below in Figure 4.

It is challenging to determine whether the categorical scales like the Likert scale, the VAS, or a combination of the two is the most practical method for obtaining subjective information regarding thermal sensation primarily because the rationale of using these differs. Some researchers argue that the VAS is a better choice because the categorical scales promote artificial feelings influenced by the wording of the options, while others suggest that the categorical scales help people describe how they feel. This creates an issue for the combined version of these two scales which also includes the wording of options like the categorical scale. A study comparing these three scales (categorical, VAS, and categorical combined with VAS) found that the categorical combined with VAS or “graphic categorical scale” had the greatest sensitivity which allowed respondents to discriminate thermal sensation at the thermal neutral zone indoor environments in both dynamic exercising and resting states. This research also showed a statistically significant relationship between

thermal sensation and mean skin temperature for the graphic categorical scale, but not for the 9-point categorical scale [25]. Results from this research are shown in Figure 5.

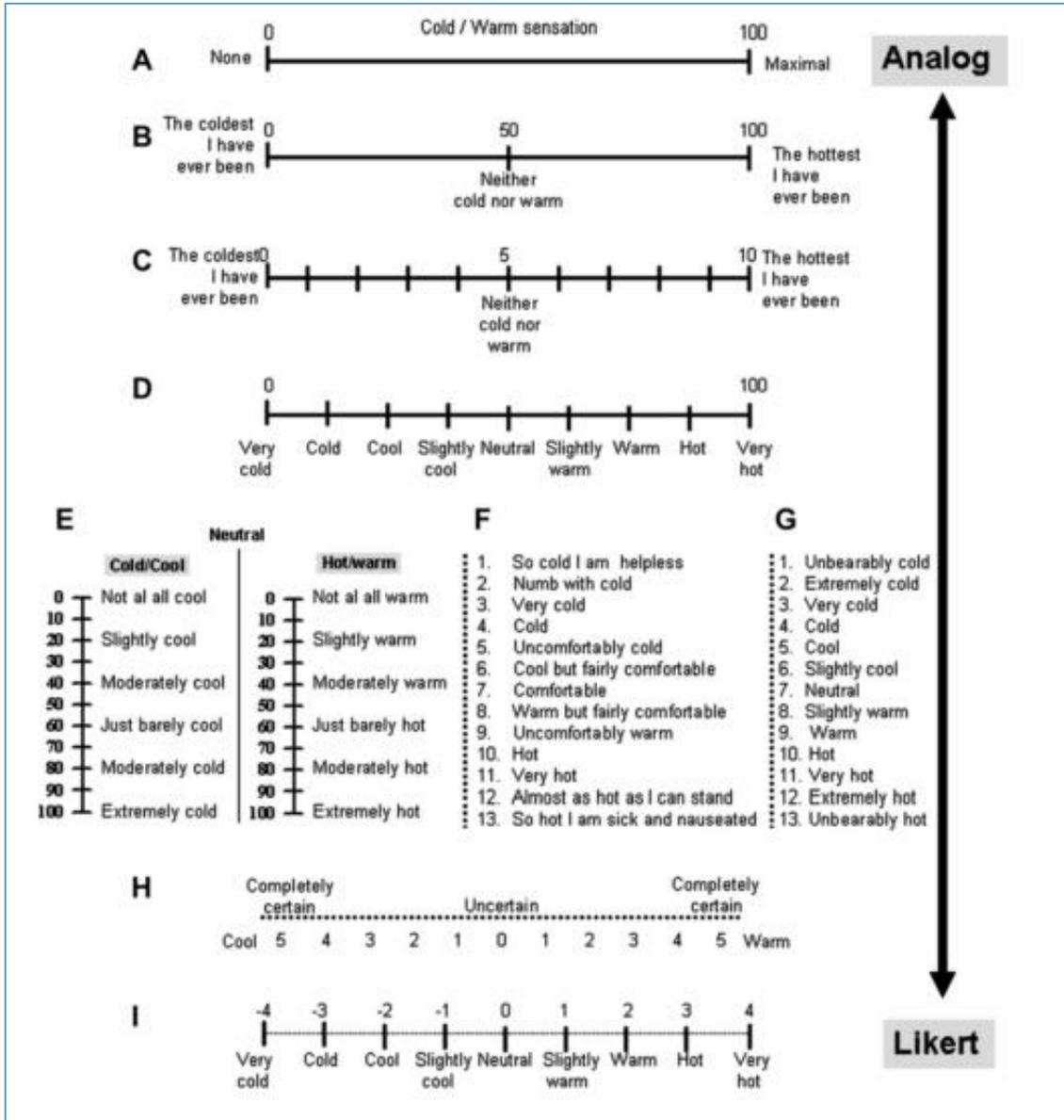


Figure 4 – Subjective Scales used for the Assessment of Thermal Sensation. (A) Unipolar standard VAS, (B) Bipolar standard VAS, (C) Bipolar numeric VAS, (D) 9-point categorical

scale combined with VAS, (E) 100-point categorical visual display scale, (F) 13-point McGinnis categorical scale, (G) 13-point Taylor categorical scale, (H) 11-point Winakor numeric scale, (I) 9-point ISO categorical scale [25]

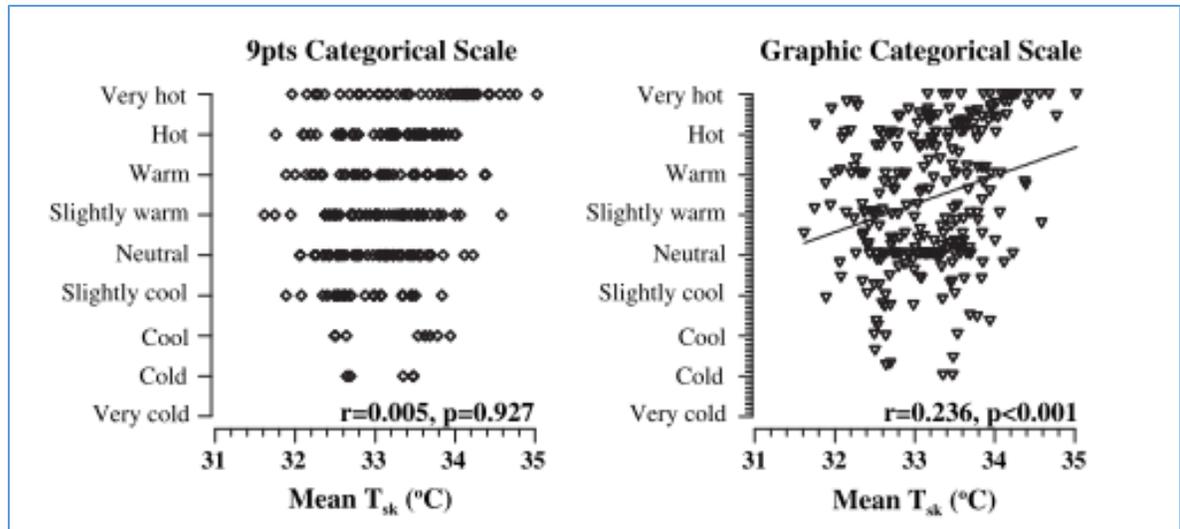


Figure 5 – Relationship between mean skin temp ( $Mean T_{sk}$ ) and thermal sensation [25]

For the present study, a graphical categorical scale similar to that of D in Figure 5 was chosen to obtain subjective thermal sensation information. This tool should be used because it can better assess the thermal sensations of resting subjects in room temperature ( $25^{\circ}\text{C}$ ) which is similar to the conditions that would be used for the present study.

Furthermore, the number of options for the respondent should be 7 or 9 like that of ASHRAE Standard 55 and ISO 10551 Standard respectively because these are the most universally accepted standards for thermal sensation.

When the Hohenstein Institute was evaluating the subjective thermal comfort of airplane seats, they followed the ISO 10551 Standard [26]. The overall climatic seat comfort

sensation, however, was based off of a 4-point categorical scale and presented as the main subjective finding. During their human seat trials, they had four young men perform a trial and evaluation of each seat two times. The test subjects wore typical clothes that would be worn during a flight (sneakers, jeans, trousers, shirt, pullover, socks, and briefs). These clothing conditions were kept constant so that the only differences from their evaluations would be due to the seat construction. The subjects were instructed to arrive at the testing facility in a calm physiological state. Before testing, the subjects wore their own personal clothing items and laid down on a sofa at room temperature for 30 minutes. Humidity and temperature sensors were attached to the subjects after this period and the subjects were dressed in the clothes described above. The test aimed to simulate real flight conditions. Thus, the test subjects sat in the seats for three hour periods without standing. Subjects were not instructed to maintain a particular posture during the test, but they were restricted using a seat belt that would be found in a standard airplane. The airplane seats where the test took place were located within a climate controlled chamber with an ambient temperature of 20.5°C and 15% RH. This is interesting because the bench-top test (described later) from this experiment used an ambient temperature of 20°C and 50% RH [26]. It is questionable for this experiment to use different environmental conditions for tests that were going to be compared to one another. For the current research, it is recommended that the environmental conditions be kept constant for an accurate comparison. It should also be noted that the subjects should be within the same general age range, clothing kept constant, and weight and height limits be set in this experiment.

Thermal sensations can differ among people even in the same environment, despite temperature sensors rendering the same. These thermal sensation differences are especially difficult for individuals to describe in a state of thermal balance which is between 20-24°C (68-75°F) and 50%RH for an average person. For example, two people that are at neutral temperatures will have a more difficult time describing their thermal sensations than if they were in extreme cold or hot conditions where their thermal sensations would likely be similar. In a Kansas State study of thermal comfort in different temperature ranges, an even wider range of comfort was described by the test subjects [27]. Five men and five women participated in this study, and results had some subjects voted “comfortable” in temperatures as low as 62°F and as high as 96°F as outliers in the results [27]. For analyzing the mattress thermal comfort and its relationship to sleeping quality, subjective methods may be challenging, as people cannot accurately describe their comfort sensation of sleeping time after they wake up [28]. Therefore, it may be more practical to have subjects remain awake and at a resting state for a subjective evaluation so that they can accurately describe their thermal sensation from the mattress. The necessity to have subjects that are awake limits the experiment test time to be somewhat short as it would be difficult to ask subjects to stay awake on a mattress for a long period of time.

### ***2.3.2 Objective methods: Bench-top test devices for thermal comfort measurement on cushioned materials***

The Standard ISO 11092:1993 and/or DIN EN 31092 Textiles – “Physiological effects – Measurement of thermal and water-vapour resistance under steady-state conditions” (sweating guarded –hotplate test) has been used in the textile industry as a determinant of thermal comfort [29]. The ASTM Standard for this test method is the ASTM F 1868 “Thermal and Evaporative Resistance of Clothing Materials Using a Sweating Hot Plate Test [30]”. This test can be done either dry or wet depending on whether the desired measureable is resistance to dry heat transfer (fabric insulation value) or resistance to evaporative heat transfer respectively. The measurements used for data analysis are obtained from a smaller test region on the face of the instrument, while the surrounding areas of the face are known as “guards”, which are used to ensure that the test region is not influenced by lateral heat flux [30]. Custom hoods can be applied to this test method to provide still-air conditions, horizontal air flow, or vertical air flow at various levels depending on the desired conditions [31]. The controlled environmental conditions used in this type of test increases the repeatability of the test results which allows for the results of different laboratories to easily compare samples [32]. The Hohenstein Institute has applied the thermoregulatory model of human skin (Skin Model) from these standards to determine the water vapor resistance of products for clients. This “Skin Model” that the Hohenstein Institute refers to is essentially a sweating guarded hotplate that is heated to 35°C to simulate the heat and moisture that is given off by sweating skin. The Hohenstein Institute suggests that realistic results which

simulate sweating skin can be obtained using the Skin Model for textiles up to 20cm in thickness [32]. This limitation in thickness capacity may make the Skin Model a suitable for various individual layers used in the construction of a mattress rather than a fully constructed mattress which would likely exceed the 20cm thickness. Equation 12 and Equation 13 below show the calculation for thermal resistance ( $R_{ct}$ ) and apparent evaporative resistance ( $R_{et}$ ) respectively. A schematic of the Skin Model is shown below in Figure 6. A “Sleep Comfort Vote for Children’s Mattresses” can be obtained from Skin Model measurements which calculate material-specific insulation, evaporative resistance, and water vapor absorbency. In turn, the Hohenstein Institute uses the Skin Model and a thermal manikin to determine the Sleep Comfort of Duvets. This test was used to provide a Sleep Comfort Vote in both cold and warm climates and a Thermal Insulation value for clients [33].

$$Eq. 12 \text{ Thermal Resistance, } (m^2C)/W: R_{ct} = \frac{T_s - T_a}{Q/A}$$

$$Eq. 13 \text{ Apparant Evaporative Resistance, } (m^2 * Pa)/W: App R_{et} = \frac{(P_{sat} - P_{amb})}{\frac{Q}{A} - \left[\frac{T_s - T_a}{R_{ct}}\right]}$$

Where  $T_s$  = Skin Temperature ( $^{\circ}C$ ),  $T_a$  = Ambient Temperature ( $^{\circ}C$ ),  $Q/A$  = Area Weighted Heat Flux ( $W/m^2$ ),  $P_{sat}$  = Saturation Vapor Pressure at Skin Temperature (Pa), and  $P_{amb}$  = Ambient Vapor Pressure at Ambient Temperature (Pa).

The apparent evaporative resistance is only calculated for non-isothermal conditions. Non-isothermal conditions (where the ambient temperature does not equal test plate temperature) are used mostly for NFPA protective clothing tests [30]. The total evaporative resistance uses isothermal conditions (where ambient temperature and test plate temperature

are both set to 35°C that is used more commonly by ISO 11092 and ASTM F 1868 is a shortened equation of the apparent evaporative resistance and is shown in Equation 14:

$$\text{Eq. 14 Total Evaporative Resistance } \frac{m^2 \cdot Pa}{W} : Tot R_{et} = \left( \frac{\Delta P}{Q/A} \right) [30]$$

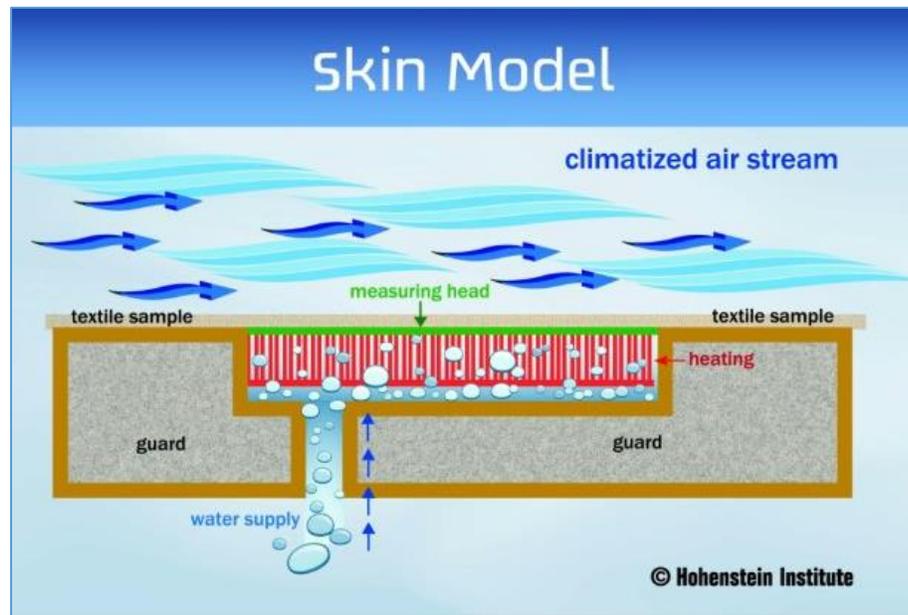


Figure 6 – Hohenstein Institute Skin Model Schematic [32]

An issue with the above test methods is that these methods do not provide an assessment of the mattress materials in the same conditions as they are used because the mattresses are not compressed or stretched as they are when people lay on them. The presence of compression may be a relevant factor for test methods concerning mattresses because this creates a more realistic situation for the obtained test results. Furthermore, a full size mattress would not fit on a standard hotplate. For these reasons, the sweating hot plate system has been modified into an inverted system. During the standard sweating hot plate

test, the test specimen is placed on top of the apparatus and the measurements are obtained, but the modified inverted version of this measurement system places the apparatus on top of the test specimen allowing for some compression to take place. This device is intended to simulate the weight and compression similar to the buttocks of a human subject which is the most compressed area of the body on a mattress. These systems are usually flat or curved depending on the contact desired on the test specimen. Shape and fit are taken into consideration in the manikin and human subject tests. The amount of compression could be adjusted to fit the weight profile of various subjects by adding or subtracting weighted plates to this device. The sweating hot plate system has been modified into an inverted system on several instances [26], [34]–[37]. In Table 2 a brief overview of these studies is given.

*Table 2 – Similar Measurement Devices and Reports of Thermal Mattress and Seat Testing*

Source:	(Bartels, 2003) [26]	(Ferguson-Pell et al., 2009) [34]	(Hänel et al., 1997) [35]	(Nicholson et al., 1999) [36]	(Ripley, Milnes, & Gregg, 2012) [37]
Indenter Face Shape:	Super-Elliptical	Buttocks Shape	Super-Elliptical (4 Shapes)	Flat	Flat
Loading Mechanism:	Pneumatic Piston Loading Rig	Pneumatic Piston Loading Rig	Pneumatic Piston Loading Rig	Weighted Plates	Weighted Plates
Amount of Force Supplied (N):	300N	300N	100N, 150N, 300N	98N	N/A
Wet/Dry Test:	Dry	Wet	Dry	Wet	Wet
Chamber Conditions (°C):	20°C	21°C 50 %RH	20°C 50 %RH	20°C 60 %RH	N/A
Test Plate Temperature (°C):	35°C	35°C	32°C	37°C	N/A
Product	Aeroplane Seat	Wheelchair cushion	Car Seat	Mattress	Mattress

Depending on the goals of the research, water can be supplied through these test systems to simulate the effects of perspiration or the test can choose to omit moisture. These tests are usually deemed “wet” tests or “dry” tests respectively. While some mattress and seating researchers have chosen to incorporate liquid into their experiments to simulate sweating [34], [37], [38], others have chosen to keep the experiments dry [26], [35] due to the inability to dispense low-rate moisture vapor at a controlled rate, and liquid sweating would indicate poor physiological function which is not to be expected during sleep or rest [26]. The present study has been conducted under dry conditions due to the unlikeliness of liquid sweating during sleep for the general population.

The schematic of one such device known as the heat and water vapour transport system (HWVTS) is shown below in Figure 7 [36].

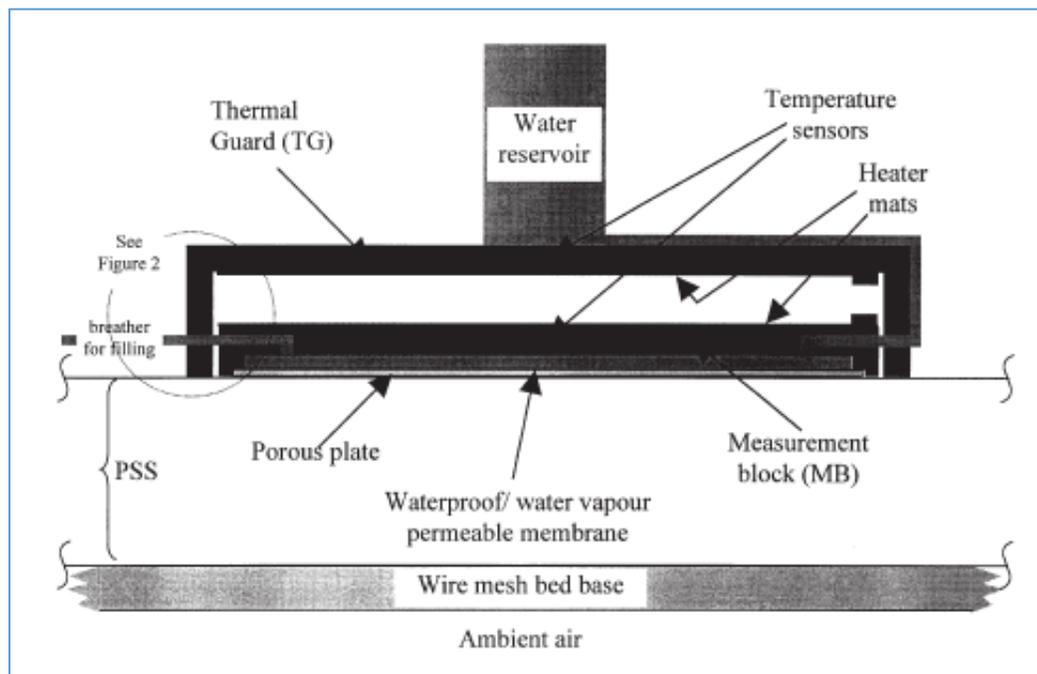


Figure 7 – Heat and Water Vapour Transport System (HWVTS) Schematic [36]

A similar advanced measurement device called the ST2-XL Test Device is made by Thermetrics (formally Measurement Technology Northwest) and can be used to evaluate thermal characteristics and vapor resistance of cushions and bedding materials such as mattresses. It is classified as a single-zone sweating skin system, but resembles an inverted sweating hot plate. It can be used to calculate thermal resistance and apparent or total evaporative resistance as in Equations 12, 13, and 14. This device lays flat on the material, mattress in this case, and has a test plate surface area of  $0.0645 \text{ m}^2$  [39]. A breathable, waterproof fabric can be placed between the device surface and the material to allow for water vapor rather than moisture to be applied to the material. The device weighs 16.78kg (37.0 lbs) and includes two external weights of 3.45kg (7.6lbs) each to simulate different levels of compression. The device is designed to provide the same compression levels as a 79.4kg (175lb) person being supported by 34% of their body surface area which is  $124\text{kg}/\text{m}^2$  ( $0.177\text{lbs}/\text{in}^2$ ). This device is able to calculate thermal resistance ( $R_{ct}$ ) and evaporative resistance ( $R_{et}$ ) using a distributed temperature sensor and the heat flux generated located within the test plate.

The thermodynamic rigid cushion loading indenter (TRCLI) was designed to measure heat and water vapor dissipation similarly to ST2-XL and the HWVTS. Instead of having a flat measurement area like these measurement devices, however, it is shaped like a buttocks and can come in two sizes. Like the ST2-XL, this device incorporates a waterproof breathable membrane to allow water vapor to reach the material surface and prevent

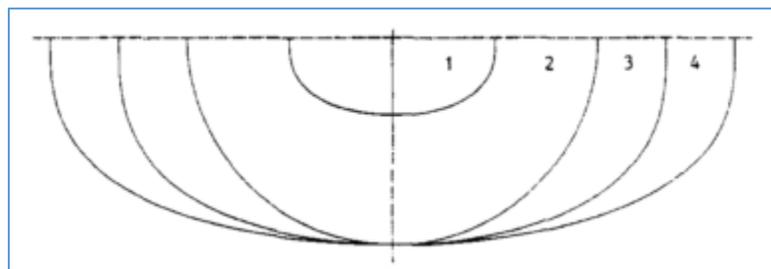
“spotting” from occurring. “Spotting” refers to visible liquid spots building up on a material at the area where the liquid is released from the device’s pores. It is important to prevent this spotting because it does not properly represent the natural perspiring of a human. For example, a human has thousands of tiny pores which release sweat whereas a device has very few, and while the amount of liquid released per area may be similar to that of a human, the concentration of the liquid is near the pores of the device. Thus, the use of a membrane on a test device allows for water vapor to pass through which creates a more natural perspiration to that of a human. This membrane is not the outer most layer like it is in the ST2-XL design. Instead, a perforated polycarbonate shell is the outer most shell. The delivery rate of water vapor can be controlled using different perforation densities in this outer shell. This apparatus was used to test seat cushions for two hour long periods. The temperature and humidity at the interface of the cushion were measured and compared after the first and second hours [34]. To increase the reproducibility of this measurement system, the device was attached to a pneumatic piston in a loading rig which would apply a 300N load to a location on the testing material. This location would be constant for each test on the cushions [34]. It is obvious that time should be taken between tests on the same cushion or mattress when using a heated and/or wetted measurement system to ensure the cushion has returned to its original conditions. When using the TRCLI, it is suggested that 12 hours is a suitable time frame between tests [34].

A group of researchers from the Swedish Institute for Fibre and Polymer Research (IFP) also developed a test device to measure thermal comfort [35]. IFP’s evaluation system

is also mounted to a loading system. The measurement area of this device is formed by super-elliptical shaped indenters. The four different shaped elliptical indenters simulate different conditions [35]. Table 3 below lists the four indenters included in this apparatus and their specifications. Figure 8 below is an illustration of each indenters shape.

*Table 3 – Various Indenters and Applications of Use [35]*

Indenter No.	Radius (mm)	Height (mm)	Field of Application
1	60	45	Tests pieces of reduced size
2	120	120	Side-lying subject
3	160	120	Sitting subject
4	200	120	Back-lying subject



*Figure 8 – Shapes of Indenters Used to Simulate Different Purposes [35]*

IFP's test method states that the indenter is heated to a constant temperature of 32°C and that the specimens should be conditioned to the testing environment for about 20 hours

prior to testing. The environmental conditions in a climate controlled chamber using this experiment are 20°C and 50% RH. This test method also uses a load of 300N similarly to the test method described by Ferguson-Pell [34]. It is noted that this loading system should be rigidly mounted to prevent tilting from occurring during the indentation process. Having an automated loading system such as this is advantageous to achieve consistent results because it allows for the data collection and test plate contact with the cushion to begin at the same moment. A test time of two hours is sufficient time to produce stationary conditions for measurement of heat flux. The calculated values during this test are  $Q_1$  which is the highest heat-flow (typically first contact with cushion), the time it takes the heat-flow to reach 60  $W/m^2$  and 40 $W/m^2$  which are labeled  $t_{60}$  and  $t_{40}$  respectively, and  $Q_4$  which is the heat-flow at equilibrium. An expected shape of a result of the test with the location of these calculated values is shown below in Figure 9. An actual result from an IFP test method for thermal comfort is shown in Figure 10 where the test device was placed on a heated car seat supplied with 15, 30, and 60W. Figure 11 shows a schematic of the described test apparatus created by IFP.

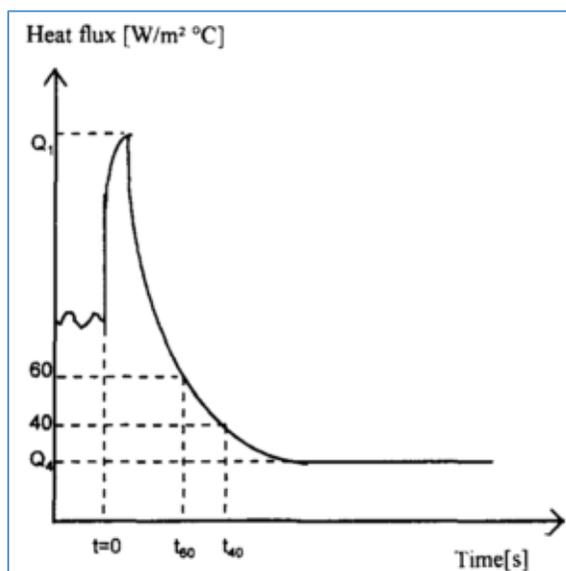


Figure 9 – Expected Result from IFP Test for Thermal Comfort [35]

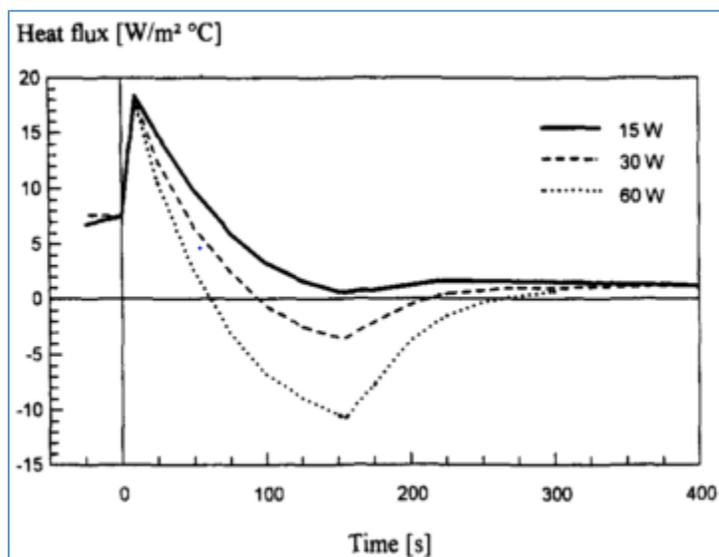


Figure 10 – Results from IFP Test for Thermal Comfort on a Heated Car Seat of 15, 30, and 60W [35]

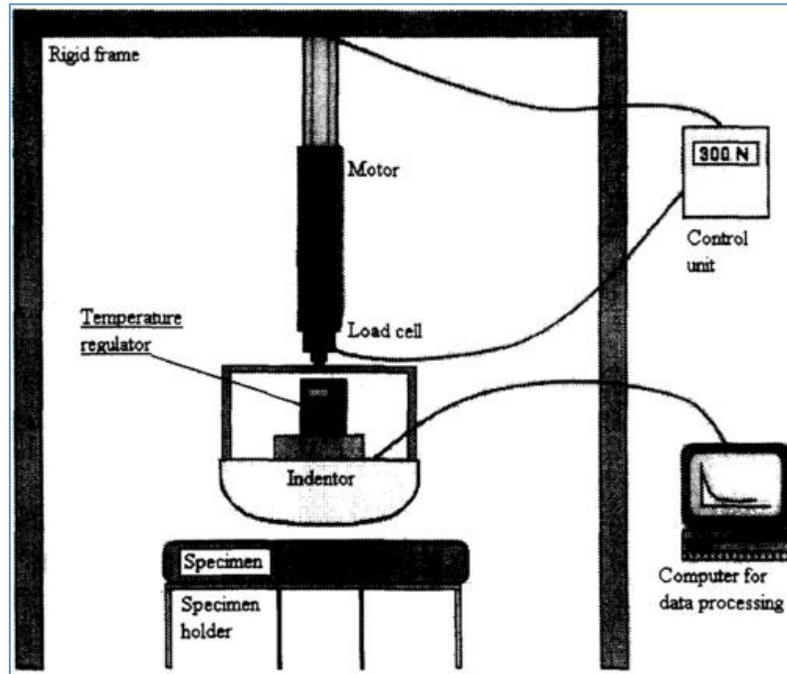


Figure 11 – Schematic of IFP Testing Apparatus [35]

The Hohenstein Institute has also modified the use of the apparatus originally designed by IFP above [26]. The stamp design has the same shape as Indenter 3 from the IFP design for simulating a sitting subject. This stamp was likely chosen because the Hohenstein Institute experiment is testing the thermal comfort of aeroplane seats. The initial heat flux ( $H_{ci}$ ) obtained at the beginning of the test simulates the thermal perception a person feels on initial contact and the steady state heat flux ( $H_{c\text{ stat}}$ ) simulates the heat transfer of a person being sitting for a longer time [26]. Both of these values were also obtained in the IFP test method. However, this test method uses the steady state heat flux value to calculate thermal resistance ( $R_c$ ) of the seat using Equation 15 below. This equation differs from the thermal

resistance in Equation 13 in that it specifically uses the steady state heat flux rather than area weighted heat flux.

$$Eq\ 15: R_c = (T_s - T_a)/H_{c\ stat}$$

Where  $T_s$  = Skin Temperature and  $T_a$  = Ambient Temperature. The test performed used the same environmental conditions in the climate controlled chamber as the IFP test, but the skin temperature used was 35°C rather than 32°C in the IFP test. This experiment tested two airplane seats. “Seat 1” was composed of a leather cover material and a foam cushion and “Seat 3” was composed of a wool cover and a knitted spacer fabric cushion. Both of the cushion materials tested were 4cm thick [26]. The thermal resistance results of this experiment using the seat comfort tester are shown below in Figure 12.

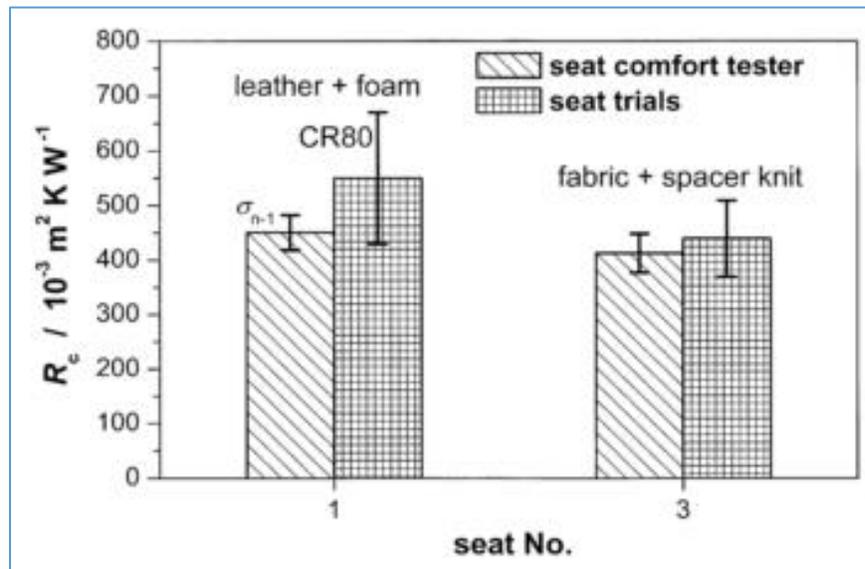


Figure 12 – Thermal Resistance Values of Seat 1 and Seat 3 Using Seat Tester and Human Seat Trials [26]

Bartels reports that thermal resistance is mainly influenced by the cushion materials [26]. Because the thermal resistance of Seat 3 is lower than that of Seat 1, sweating would be less likely to occur on Seat 3 than Seat 1. The initial heat flux (when the seat comfort tester first came in contact with the seat) is mainly influenced by the cover materials. In this experiment, the leather cover had a significantly higher value than the wool fabric cover. This means that the initial thermal sensation of getting seated would be cooler for the leather than the wool fabric. The results obtained using the seat comfort tester had a poor correlation to data obtained from a seat trial on human subjects with the same seat constructions indicating that this procedure cannot provide an accurate assessment of thermal comfort of airplane seats [26].

Recently, Leggett and Platt (L&P), a well-known mattress industry supplier, performed a similar bench-top test to compare a polyurethane memory foam mattress to a mattress with gel in the comfort layer of the mattress for cooling properties [40]. The test was performed in L&P's in-house lab and compressed the beds' surfaces using an aluminum plate heated to an undisclosed temperature with a thermocouple located between the plate and the surface of the mattress to measure surface temperature. L&P state that the results showed that the gel mattress was cooler by an average of 2.8°C (5°F) than the polyurethane memory foam mattress after more than 4.5 hours. The company also stated that similar results were obtained through test repetitions with various configurations [40]. Although the company does not state the exact type of measurement system that was used for this experiment, it is to be assumed that a device similar to the inverted sweating hot plate was

used due to compression being introduced to the mattresses. The company did not report any temperature or humidity measurements for the different layers of the bedding system, which would be possible with the ST2-XL measurement device.

The ST2-XL was chosen as the benchtop test device to assess the thermal comfort of mattresses in the present study. This test device is capable of operating in both the dry and wet states and is able to control the power supply to the test region via heat flux or surface temperature providing the different options for test method development. Furthermore, the three zones of the test device ensure that the test region is undisturbed from external factors while in operation.

### ***2.3.3 Objective methods: Manikin***

A manikin is a model of human body used for the purpose of medical, educational and engineering evaluations. In the study of thermal comfort, a manikin can stimulate the responses of human beings in different environment. The use of thermal manikins is increasing, as they provide a reproducible evaluation of thermal comfort that can offer a high level of repeatability. Manikins can provide relatively quick and accurate measurements for assessing comfort of apparels and indoor environments [41]. For the purposes of this study, the manikin could provide insight to the comfort of mattresses with quantifiable data and measurements that are difficult to obtain with a human subject evaluation method. Although advanced thermal manikin systems are expensive, they offer freedom from human wear trials

which can be expensive as well. However, thermal manikins also have limitations, such as the absence of vasoconstrictor response initiated in human skin when cooled.

Manikins can be classified in terms of the materials, numbers of segment, and their functions. Table 4 lists manikins that may be relevant in the present study.

*Table 4 – List of Potentially Useful Manikins for Mattress Study*

Multi-segment	Plastic	Digital	Movable
Sweating manikin	Aluminum, Copper	Digital	Movable
Female manikin	Plastics	Digital, comfort regulation mode	Movable
Breathing thermal manikin	Plastics	Digital, comfort regulation mode	Movable, breathing simulation
Virtual, computer manikin	Numerical, geometric model	Heat and mass transfer simulations	Articulated
Sleeping Computational Thermal Manikin(SCTM)	Numerical, Cuboid Shape	Heat transfer simulations	Immobile [7]

For a mattress comfort study, multi-segment manikins are essential for the analysis of local skin temperature. This is important because skin temperature is not uniform throughout the different distal and proximal regions and can also vary depending on the time of day and level of activity [42]. Experimental research should be based on a thermal manikin in a climatic chamber, adapted from recent studies on comfort of bedding system and sleepwear. In the present study, the metabolism rate is proposed to be as low as 40W and external work  $W_{\text{ext}}$  equals 0 W because the body is relatively motionless during sleep [10].

Although there is no current standard test method available for the measurement of thermal comfort on a mattress, the test should differ very little from how they are usually used and the functions of the thermal manikin remain the same. Thermal manikins are usually uniformly heated to 35°C to simulate human skin temperature. In the case of evaluating mattresses and bedding systems, the manikin is placed in the supine position on the bed and covered with bedding to a determined area of coverage if desired for a given amount of time (usually 2-4 hours). During this time, the amount of energy required to keep the manikin at the desired temperature is measured [28].

Using a thermal manikin to assess the mattress comfort based on the measured values from the thermal manikin will produce metrics such as total insulations, skin temperature, total heat loss, etc. In order to meet the needs of the research, the use of a multi-segment manikin with temperature sensors is suitable in the mattress comfort study. Computer control systems approximately simulate the skin temperature distribution of a human being.

Temperature sensing elements are distributed in different distal and proximal regions on the manikin's surface.

Experiments need to be carried out in a climatic chamber to ensure constant environment variables. The thermal manikin is placed with a supine position on a sample mattress, which is located in the middle of the chamber. It would be ideal that the manikin technology could account for the physiological changes of skin temperature that occur in a human when switched from an upright position to the supine position. This would be beneficial because most people sleep in the supine rather than upright position and this is the position used in most manikin tests regarding mattresses. The temperature of each segment of the manikin is controlled by a sophisticated system. The mean skin temperature of the experiment should be decided carefully with considering the optimal thermal comfort model since  $T_{sk}$  is an important factor that influences thermal sensation.

Despite the influencing factors from environmental variables, heat loss from a naked thermal manikin can be used to describe the thermal sensation of human during sleep and rest. Some researchers have used the total thermal resistance ( $R_t$ ) and the total insulation value ( $I_T$ ), which is often adapted from the research of clothing, to describe the thermal comfort of bedding system. Thermal resistance and insulation are both common values to obtain when using a thermal manikin because they indicate how much resistance there is to heat flow [16]. Equation 16 shows the calculation of total thermal resistance and Equation 17 shows the calculation of total insulation value.

$$Eq\ 16: Total\ Thermal\ Resistance,\ (C * m^2) / W: R_t = \frac{\bar{t}_{sk} - t_0}{H_{sk}} = \frac{\sum(a_i t_{sk,i}) - t_0}{\sum(a_i H_i)}$$

$$\text{Eq 17: Total Insulation Value, Clo: } I_T = KR_t$$

Where  $t_{sk}$  = mean skin temperature ( $^{\circ}\text{C}$ ),  $t_0$  = operative temperature ( $^{\circ}\text{C}$ ),  $H_{sk}$  = whole body heat flux ( $\text{W}/\text{m}^2$ ),  $a_i$  = area fraction of segment related to whole body area,  $t_{sk,i}$  = local skin temperature of segment ( $^{\circ}\text{C}$ ),  $H_i$  = local heat flux of segment ( $\text{W}/\text{m}^2$ ), and  $K$  = constant 6.45 ( $\text{clo W}/(\text{m}^2 \text{ } ^{\circ}\text{C})$ ). The first total thermal resistance equation shows the overall calculation for thermal resistance for the entire manikin, while the second equation shows how  $t_{sk}$  and  $H_{sk}$  are calculated if a segmented manikin is used which can also be useful for looking at certain regions of the body i.e. the back.

There are some related standards that are helpful to the present study using thermal manikins, shown as Table 5.

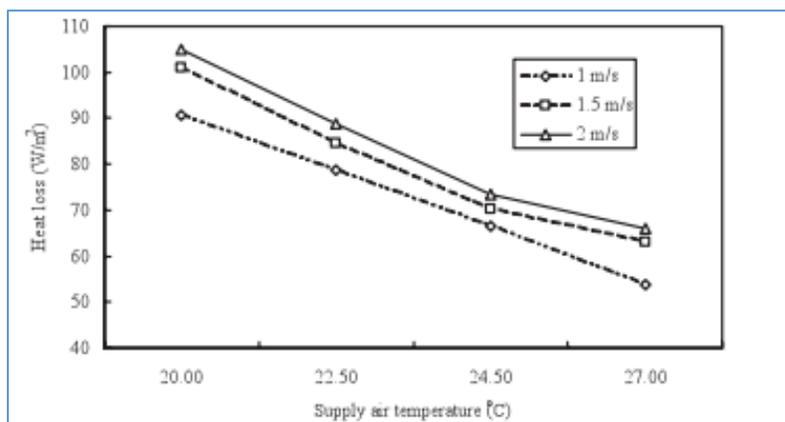
*Table 5 – Related Standards of Thermal Comfort Study Using Manikins [41]*

Standards	Description
ISO 9920	Estimation of the thermal characteristics of clothing
ASTM F1291	Standard method for measuring the thermal insulation of clothing using a heated thermal manikin
EN-ISO 15831	Thermal manikin for measuring the resultant basic thermal insulation
ISO 7730	Determination of the predicted mean vote and the predicted percentage dissatisfied indices and specification of the conditions for thermal comfort

The Institute of Environmental Research at Kansas State University designed a test which utilized thermo-regulated manikins to measure the rate of heat energy transfer through

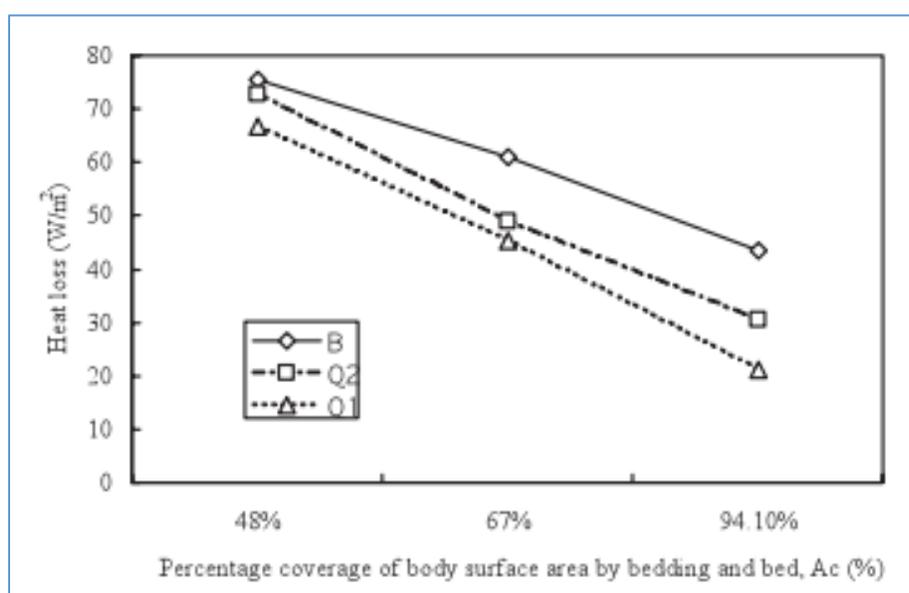
a given surface, or heat flux, to compare a memory foam mattress to a gel mattress for L&P [40]. During the test, the thermo-regulated manikins were heated to 35°C (95°F) and placed on the beds for four hours. Results showed that the gel mattress provides a 113% greater heat flux in the first hour than the polyurethane memory foam comfort layer [40].

It is obvious that the effectiveness of heat loss through convection will vary depending on the amount of coverage provided by the bedding system. Thus, it is important to note the differences in covered manikin trials versus naked manikin trials. In a study by Pan, different air supply temperatures were applied to a female naked sleeping thermal manikin on a mattress and the heat loss from the body was measured for different air velocities. This manikin was set to have a mean skin temperature of 31°C in the hands and feet, and 35°C for the remaining areas to give a whole body mean skin temperature of 34.6°C. The area coverage of this manikin is suggested to be 23.3% provided by the mattress alone [7]. The results of the study are shown in Figure 13 below.



*Figure 13 – Heat Loss from Three Air Velocities at Varying Air Temperatures on a Nude Female Thermal Manikin [7]*

The same study performed by Pan demonstrated how a bedding system could significantly affect the amount of heat loss experienced by a covered sleeping thermal manikin depending on percentage of the manikin covered by the bedding and the insulation level of the bedding. The results of this demonstration were provided from a supply air flow rate of 2 m/s and a supply air temperature of 22°C. The test was performed on a conventional mattress. The results of this study are shown below in Figure 14.



*Figure 14 – Female Thermal Manikin Heat Loss from Three Different Beddings at Varying Surface Body Coverage [7]*

The images below in Figure 15 show the three different areas of coverage provided by the bedding to the thermal manikin which were used in the study.



Figure 15 – Examples of the Area Coverage ( $A_c$ ) 48.0%, 67.0%, and 94.1% [7]

A similar thermal manikin study which used the same three bedding materials as the experiment above, but also included two different mattress types found that mattress type had a significant effect on the total insulation values ( $I_T$ ) of the bedding systems [16]. The effect that the mattresses had on the total insulation values increased as the area covered ( $A_c$ ) by the bedding increased. Their results showed that when a light summer quilt (Summer Quilt 2) was used in a bedding system with 94.1%  $A_c$ , a conventional, thicker mattress had a  $I_T$  of 3.03clo while a thinner, Chinese traditional *Zongbang* mattress had an  $I_T$  of 2.50clo. This  $A_c$  of 94.1% gave a difference of 0.53clo or 17.5% between the two mattresses. When this  $A_c$  was decreased to 48.0%, the conventional mattress and *Zongbang* mattress had lower  $I_T$  values of 1.16clo and 1.07clo respectively. This  $A_c$  of 48.0% gave a much lower difference of 0.09clo or 7.8% between the mattresses [16]. The results of this experiment where the thermal manikin is not wearing sleepwear (nude condition) is shown in Figure 16 below. Where M1 is the conventional, thick mattress, M2 is the *Zongbang* mattress, B is a very light

blanket, Q2 is a light summer quilt (Summer Quilt 2), and Q1 is a thicker summer quilt (Summer Quilt 1).

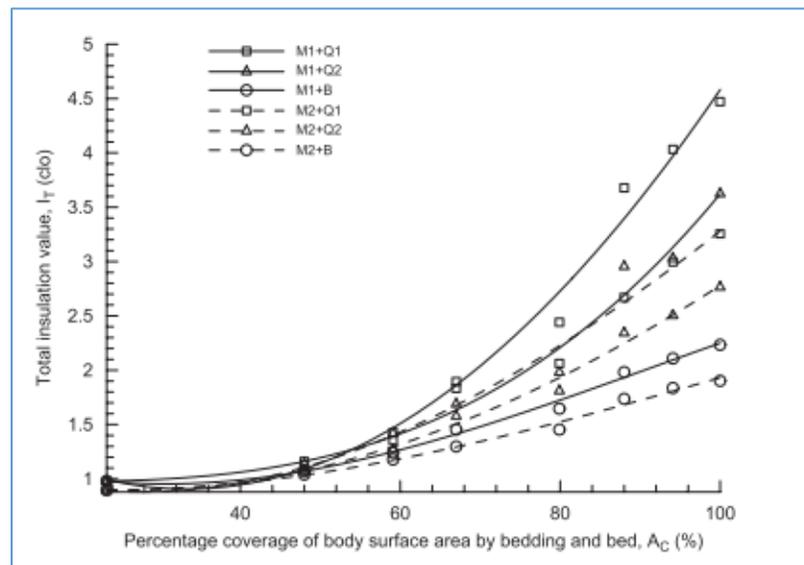


Figure 16 – Total Insulation Value,  $I_T$ , of Bedding Systems with Different Area Coverage,  $A_C$ , with No Sleepwear [16]

This difference in  $I_T$  between the mattresses was also shown to increase as the insulation of the sleepwear increased even when no bedding is used. This is shown in Figure 17 below, where S1 is a full-zip (long sleeve) sleepwear and S2 is half-zip (short sleeve) sleepwear. The parameters from this experiment are calculated from at least 30 steady-state points of data, but the time to reach steady state for each test is not provided.

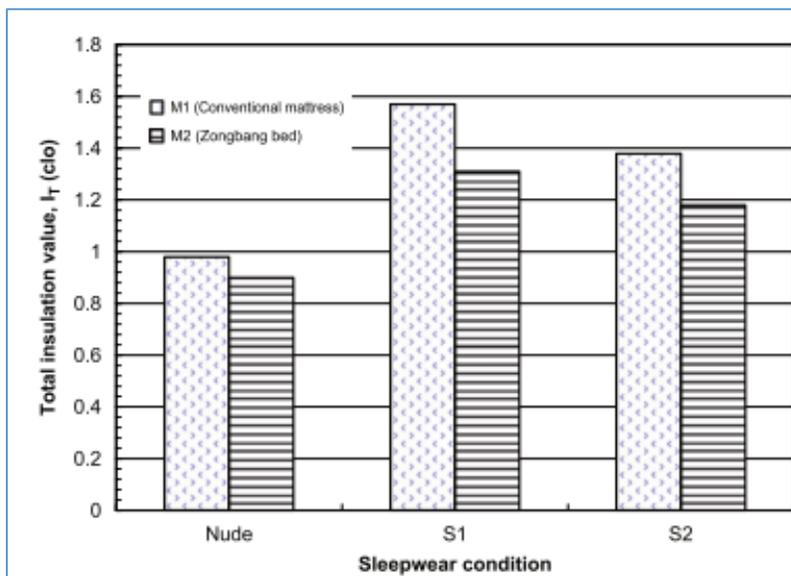


Figure 17 – Total Insulation Value,  $I_T$ , on Two Different Mattresses with Different Sleepwear Conditions and No Bedding,  $A_c = 23.3\%$ , [16]

### 2.3.4 Objective Methods: Study on Human Body

Participants of a variety of ages, genders, weight, and height may be involved in the human subject evaluations. These characteristics can cause significant differences in both thermal comfort and sleep quality. Participants should be voluntary and procedures should be introduced clearly to the participants. For mattress comfort and sleep comfort, alcohol, caffeine, and other food, and variation in physical activity (exercise) that may alter the trial results should be restricted [43]. In addition, sleep garments and materials should be kept constant as well.

The most common approach to observe human thermal comfort is to analyze the skin temperature change during the experiment. With participants lying on a sample mattress, skin

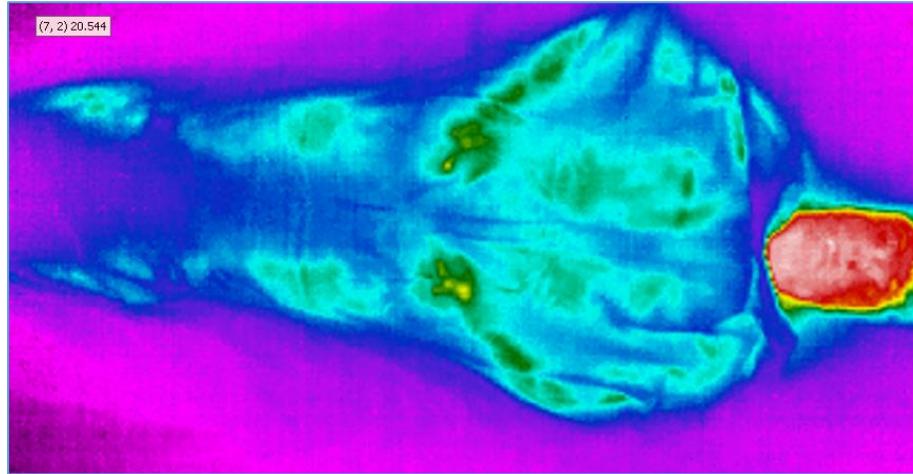
temperature on certain body parts is continuously recorded during their sleep or resting. According to ISO 9886:2004, the skin temperatures are measured on eight body sites (forehead, right scapula, left upper chest, right arm in upper location, left arm in lower location, left hand, right anterior thigh and left calf).

Hardy and DuBois's Seven-Point Method for calculating a mean skin temperature has been used in mattress research [44]. This method uses a weighted approach based on seven different local temperatures on the human body. The seven local regions measured are the forehead, abdomen, forearm, hand, thigh, calf, and foot.

Other researchers have chosen to use as little as four local regions for calculating the mean skin temperature [45]. A study on the sleep quality at different ambient temperatures used this four-point method with local skin temperature measurements at the chest, upper arm, anterior thigh, and anterior calf.

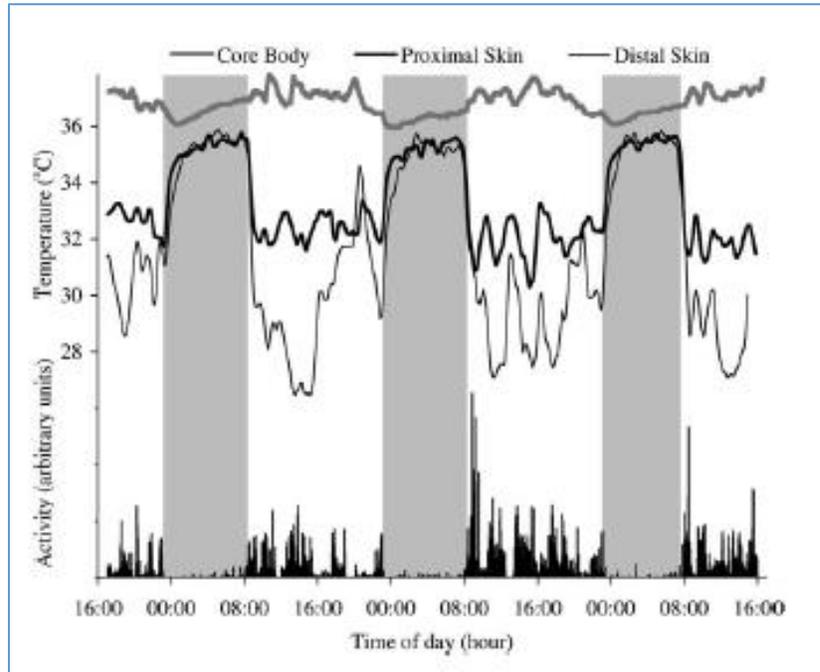
For the study of mattress thermal comfort, the differences of skin temperatures between body parts are especially important. IR images may be helpful to demonstrate the difference of surface temperature. L&P conducted a three-phase research study which utilized thermal imaging to validate the 'cool factor' of the buckling gel used in some of the comfort layers of their mattresses [40]. In the study, human test subjects were instructed to lie on the beds for two hours in the supine position. After the two hours, subjects were removed from the bed and thermal images were taken of the mattress after ten seconds of the subjects being removed. The thermal images from the study showed that the gel mattresses were cooler compared to the polyurethane memory foam-only models [40]. An example of

an IR image with human subject on a mattress is shown in Figure 18. A drawback of this method is that the IR camera is only capturing the heat differences that are occurring on the surface of the mattress. Furthermore, the pressure and heat distribution of the different regions of the body would be different for each individual. Adding to this issue, when the subject removes himself/herself off of the bed, the image will show variation because of convective heat transfer and the release of the compression which would vary depending on the region of the body and individual. Another flaw of this test method is that it only includes one IR image. This method of using an IR camera would be much more informative if multiple images were used to understand how the mattress responds to heat. Because mattresses are thick and the mattress has been subjected to body heat for two hours allowing the heat to diffuse deep into the material, images over a wider time span would be more practical. The experimental conditions surrounding the human subjects were not well defined this this study. It would helpful to know the ages, weight, gender, activity level before the test, and skin temperatures before/after the test. For the present study, this method does not seem useful as the data will vary considerably due to the aforementioned reasons.



*Figure 18 – Thermal Image of Mattress during Human Study*

There have been many claims for the most comfortable skin temperatures in sleeping conditions during human studies. Bischof et al.'s sleep subjects found that the most comfortable skin temperature was approximately 32.5°C [6]. This is within the range of 31.5-32.9°C found by Huang when researching the optimal skin temperature for thermal comfort sleeping bags [10]. Both of these hypothesized skin temperatures are within the typical temperature of bedding during sleep which is 32-34°C with 40-60 %RH [9], [46]. It has also been reported that a skin temperature of >35°C will cause thermal discomfort and a reduction and sleep quality [10]. Van Someren and colleagues determined that the distal and proximal skin temperatures stabilize close to 34°C after sleep onset occurs [42]. Figure 19 shown below illustrates the core, proximal skin, and distal skin temperatures over three days related to the subject's time in bed and activity levels [42].



*Figure 19 – Three Day Core, Proximal Skin, and Distal Skin Temperatures with Activity Monitoring [42]*

The thermal neutral skin temperature of a sleeping person is considered to be  $34.6^{\circ}\text{C}$  as calculated by Fanger's linear regression equation which determines optimal thermal comfort. Fanger's equation shown as Equation 18 is presented below.

$$\text{Eq 18: } T_{sk} = 35.7 - 0.0275(M - W)$$

Where  $M$  is the metabolic rate of a sleeping person and considered to be  $40\text{W/m}^2$ , while  $W$  is the external work performed, considered to be  $0$  for a sleeping person [47].

The ambient or air temperature is also important to investigate when considering thermal comfort. In order for there to be an effective flow of thermal energy from the body to the environment, the skin temperature should be greater than the environmental

temperature. When the environmental temperature is greater than the skin temperature, the body can only dissipate heat by evaporation [48]. The microclimate of the bed is directly related to thermal comfort during sleep; however, some studies conclude that the thermal environment outside the microclimate is irrelevant to the thermal comfort of a sleeping person [6]. The optimal thermal neutral temperature for a sleeping person varies upon other factors including but not limited to the presence of airflow, the clothing worn by the person, and the insulation level of the bedding [10], [47]. Previous studies report that the thermoneutral temperature for covered sleeping conditions is between 20-22.2°C, while the thermoneutral temperature for naked sleeping conditions is 28-32°C [16]. However, studies by Miyazawa determined that ambient temperature between 11-29°C do not significantly affect the quality of sleep [49]. In our evaluations, it will be important to keep air temperature as well as coverage constant.

Sleeping environments with high humidity and high temperature can put heat stress on the human body by decreasing the evaporative sweat efficiency [50]. This heat stress can, in turn, reduce the amount of REM and slow wave sleep, and increase the amount of wakefulness. Airflow can improve the thermal sensation and comfort in these warm, humid conditions by increasing the convection heat loss which will decrease the skin temperature and the sweat rate of the sleeping individual [50]. It is also important to note that the effective convection area of a human body changes with direction of the airflow; it is smaller when the airflow is perpendicular to the major axis of the human body and largest when parallel to the major axis of the human body [16]. Other studies suggest that convection is an

ineffective method of heat loss because the bedding covers block the airflow from coming in contact with the body [42].

The increased sweat rate experienced by the human body during sleep is a mechanism of evaporative heat loss. This sweat rate increases during slow wave sleep (SWS) and decreases during REM sleep and wakefulness as shown in the figure below [51]. The delayed onset of sweating and decreased sweat rate during REM sleep results in lowered evaporative heat dissipation and reduces the heat tolerance of the human body. The decreased sweat rate that occurs during REM, as shown in Figure 20 below, is observed prior to the onset of the REM stage [9].

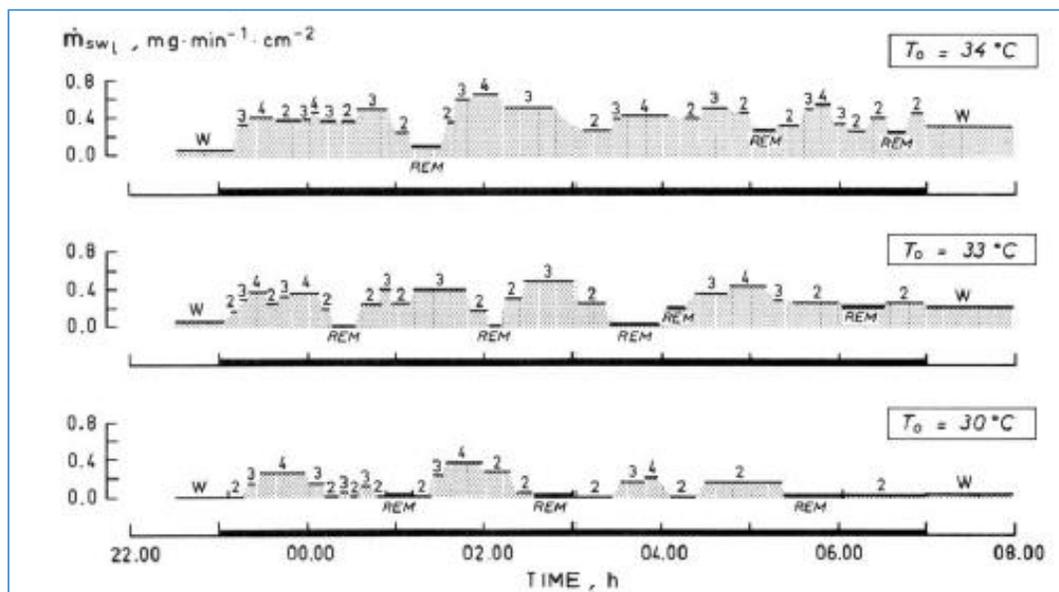


Figure 20 – Human Sweat Rates throughout Sleep Stages at Different Operative Temperatures [51]

## **2.4 Conclusions**

A reasonable range of literature searching was accomplished to contribute this review paper. When reading the research work by the pioneers and experts in ergonomics and medication, it has been found that a combination of several methods was adapted wisely regarding their research purposes. Therefore, to carry out the present study on mattress thermal comfort, the approaches introduced above should be combined to cover the weakness of each other. The study can be further improved by finding out the correlation of pressure distribution and its effect on thermal comfort.

The ST2-XL and segmented thermal manikin were chosen as the test devices for the present study. The ST2-XL is capable of operating in both the dry and wet states and is able to control the power supply to the test region via heat flux or surface temperature providing the different options for test method development. Furthermore, the three zones and flat surface of the test device ensure that the test region is undisturbed from external factors while in operation. The segmented thermal manikin was also included in this research because it can determine localized thermal properties at different body regions.

## **CHAPTER 3: A Comparison of Mattresses Using a Thermal Seat Tester**

### **3.1 Introduction**

Bed mattresses provide an important structure to enable a good night's sleep. The most important aspect of mattress comfort is not only the pressure distribution to the human body but, also the thermal comfort of sleep [1], [10], [16]. In addition to the thermal comfort

during the sleep period, which is typically 7-8 hours, the initial temperature effects of the bedding in general and the mattress specifically are relevant for comfort. As many people reside in their bed some time prior to falling asleep, e.g. reading or watching TV, this initial thermal comfort has received very little attention. Furthermore, no good methods exist to assess the thermal and heat exchange aspects of mattresses for this initial period.

The measurement of heat transfer properties is not a new concept to the textile industry per se, particularly the clothing industry. Two common instruments used to determine these properties in clothing and textile systems are the sweating guarded hotplate and the (sweating) thermal manikin. These two measurement systems operate similarly, but differ in strengths and weaknesses. In standard procedures, these measurement systems operate in a mode that sets the temperature difference and measures the heat flux through the fabric system. Alternatively, these methods could be set to a mode where a constant heat flux is provided and the resulting temperature difference is measured. The sweating guarded hotplate is specifically geared towards accurately measuring the fabric properties, but its limitation is that it does not introduce the fit or drape that might be associated with the fabric when it is worn by a human [30]. The thermal manikin is more useful for analyzing thermal properties of the clothing garments and does introduce the fit and drape that might be experienced by a human.

While both of these systems could be useful for analyzing the thermal properties of mattresses, cushions, or other bedding materials, the present study will focus on the sweating guarded hotplate system, as this system provides a better interpretation of the material

components and how their differences may impact heat flow from a human body. As sweat rates are generally low in comfortable sleep environments, the experiments described here have focused first on the evaluation of dry heat loss.

The two dry test methods investigated [26], [35] were both used to determine differences in thermal properties of car seats. Bartels found slight differences using a seat tester between two aeroplane seats that utilized different materials and found that these differences were perceived by human subjects through subjective evaluation. However, these differences found by the seat tester were not statistically significant from each other [26]. The test method of Hänel et al. states that it has been “useful in optimizing the location of the heating element for rapid initial heating when using different foams in order to maintain a pleasant contact pressure against the seat,” but the report does not provide any evidence of the apparatus’ ability to differentiate between thermal properties of cushioned materials [35]. Hänel et al. differed from Bartels in that the test method included variables to represent the time where the test device reached 60 and 40 W/m<sup>2</sup>. These variables, however, would not be a practical indication of the steady state thermal properties of the materials, because thick materials like mattresses take much longer than an hour to reach steady state since there is greater distance for the heat to travel. Furthermore, neither of these experiments investigated the impact that different ambient temperatures would have on the thermal properties of the cushioned materials which is necessary when considering the wide range of temperatures to which households of different regions can experience in a calendar year.

This paper reports results of an experimental study comparing the thermal properties of three different mattresses using an inverted guarded hotplate system. Three different ambient temperatures (16°C, 20°C, 24°C) were used to understand the influence that temperature would have on the thermal properties of the mattresses. The comparison will seek to find objective thermal differences in the mattresses in both the short-term and long-term by analyzing the surface temperature, heat flux generated, and thermal resistance of the test device, to relate those differences to the mattress construction or materials.

## **3.2 Experimental Method and Materials**

### ***3.2.1 Materials***

The experiments were conducted in an environmental chamber on a bedding system. The location of the bedding system remained consistent throughout the series of experiments to control for local air flows. The experiments in the environmental chamber were carried out at three different ambient temperatures: 16°C, 20°C, and 24°C  $\pm$  1°C at a relative humidity of approximately 65%  $\pm$  5% and wind speed of 0.4 m/s.

The bedding system consisted of an adjustable mattress frame, a box spring, a mattress, and a cotton fitted sheet. The bedding system setup remained consistent throughout the series of experiments other than changing out the mattresses. The mattresses used for this study were all twin size mattresses. The specifications for the three mattresses (A, B, and C) are shown in Table 6 below. Mattress A was a polyurethane (PU) foam mattress, Mattress B

was an innerspring mattress, and Mattress C was a PU foam mattress enhanced with phase change materials (PCMs).

*Table 6 – Mattress Specifications for Seat Tester Testing*

Experimental Name:	Mattress A	Mattress B	Mattress C
Mattress Construction:	PU Foam	Innerspring	PU Foam with PCMs
Area Dimensions (cm): (L x W)	185 x 94	202 x 97	193 x 91
Thickness (cm):	25	20	31
Weight (kg):	18.15	14.95	27.20
Density (g/cm <sup>3</sup> ):	0.0417	0.0381	0.0499

The measurement device ('test device') used for the present study was the ST2-XL developed by Thermetrics in Seattle, Washington. It is classified as a single-zone sweating skin system, but largely resembles an inverted sweating hot plate to allow placement on top of the mattress. Ten temperature and relative humidity ambient sensors are included in this system. One of these sensors is used with the software to calculate the  $R_{ct}$  and  $R_{et}$ . The other nine sensors can be placed in different levels of material, or bedding

system in this case, to evaluate the microclimate and other conditions. This measurement device also includes a frame structure which, when placed under the sheets of a bedding system, can produce an airspace where the microclimate can be evaluated. Figure 21 and Figure 22 below show the test plate area and an above view of the device respectively. [39]. Currently, there is no standard test method for using this device to evaluate mattresses for thermal and moisture properties.

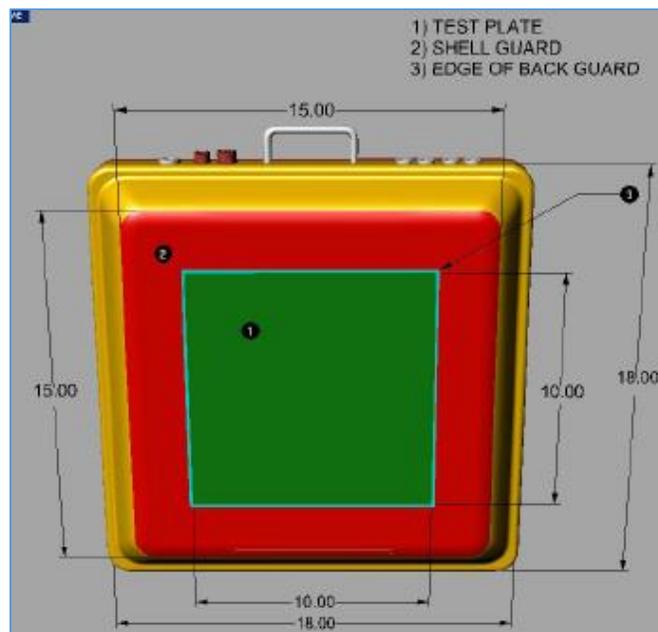


Figure 21 – Test Plate and Shell Guard of ST2-XL [39]

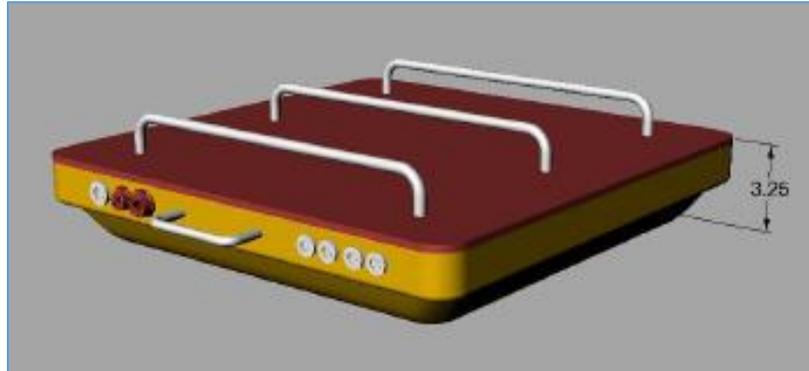


Figure 22 – Frames and Width of ST2-XL [39]

The device consists of three major zones: the isothermal test plate, an internal heated guard zone, and an external heated thermal shell. The internal heated guard zone and external heated thermal shell ensure that all the heat that is added to the test plate is transmitted through the sample material that is being tested. A distributed heater, distributed temperature sensor, and distributed heat flux sensor are embedded within the test plate to obtain accurate measurements. In the experiments conducted here, the three zones were temperature controlled and set to 35°C to represent the temperature of human skin according to the ASTM standard F1868 [30]. The experiments yielded three important variables through the control software which were heat flux generated ( $\text{W}/\text{m}^2$ ), test plate temperature ( $^{\circ}\text{C}$ ), and thermal resistance ( $^{\circ}\text{Cm}^2/\text{W}$ ). The calculation performed by the control software to obtain the thermal resistance ( $R_{eff}$ ) is shown in Equation 21.

$$\text{Eq. 21 Thermal Resistance, } (m^2C)/W: R_{eff} = \frac{T_s - T_a}{Q/A}$$

Where  $T_s$  = Skin Temperature ( $^{\circ}\text{C}$ ),  $T_a$  = Ambient Temperature ( $^{\circ}\text{C}$ ), and  $Q/A$  = Area Weighted Heat Flux ( $\text{W}/\text{m}^2$ ).

In Equation 21,  $R_{\text{eff}}$  is used instead of the standard  $R_{\text{ct}}$ , because the actual heat loss from the hot plate may be limited by an internal mattress temperature that doesn't necessarily equal the air temperature.

### ***3.2.2 Experimental Procedure***

The mattress frame, box spring, and mattress were placed in the middle of the environmental testing chamber and a cotton fitted sheet was secured to the mattress being tested. The sheet was adjusted such that there were no wrinkles and the test region had a smooth surface. Before testing, the testing materials were conditioned to the desired testing environment for at least 20 hours and all three of the test device's heating zones were preheated to  $35^{\circ}\text{C} \pm 0.01^{\circ}\text{C}$ . The test was initialized using the control software and the test device was immediately and carefully placed on the middle of the mattress with the plate region flat on the surface of the mattress with no regions of overhang. The experiment was then allowed to run undisturbed in the chamber for at least 2 hours and maximally up to 10 hours. When the test time was completed, the test was ended on the control software and the test device was removed from the mattress.

### ***3.2.3 Data Analysis***

After completing the experiments, graphs of the important measured variables (Heat Flux Generated, Surface Temperature, and Thermal Resistance ( $R_{\text{eff}}$ )) were created to obtain a visual understanding of the data trends in the experiments.

While the graphs provided sufficient understanding of the data in the initial hours of the experiments, they could not provide complete steady state values because of the length of time required to reach this state. For this reason, the curve fitting tool in MatLab® R2014b by MathWorks® was used to obtain an estimate of the steady state  $R_{\text{eff}}$  values and the time required to reach the estimated steady state. Due to the type of transient conditions found in the initial thirty minutes (discussed later), the data in the initial thirty minutes was omitted from the data analysis using the curve fitting tool to allow curve fit of the longer term heat flux effects on the mattresses. The equation used to calculate the curve fit is shown by Equation 19.

$$\text{Eq 19: } y = f(x); \text{ where } x = a * (1 - ce^{-x/\tau})$$

Where  $a$  = Steady State  $R_{\text{eff}}$  ( $^{\circ}\text{C} \cdot \text{m}^2/\text{W}$ );  $\tau$  = Time Constant Indicating Time to Reach Steady State  $R_{\text{eff}}$  (Minutes); and  $c$  = a Scaling Constant to Fit the Data Optimally.

The statistical significance of the notable data trends obtained from both the graphs in and the curve fitting tool were calculated by using one-way ANOVA tests in JMP Pro 11 by SAS.

### 3.3 Results

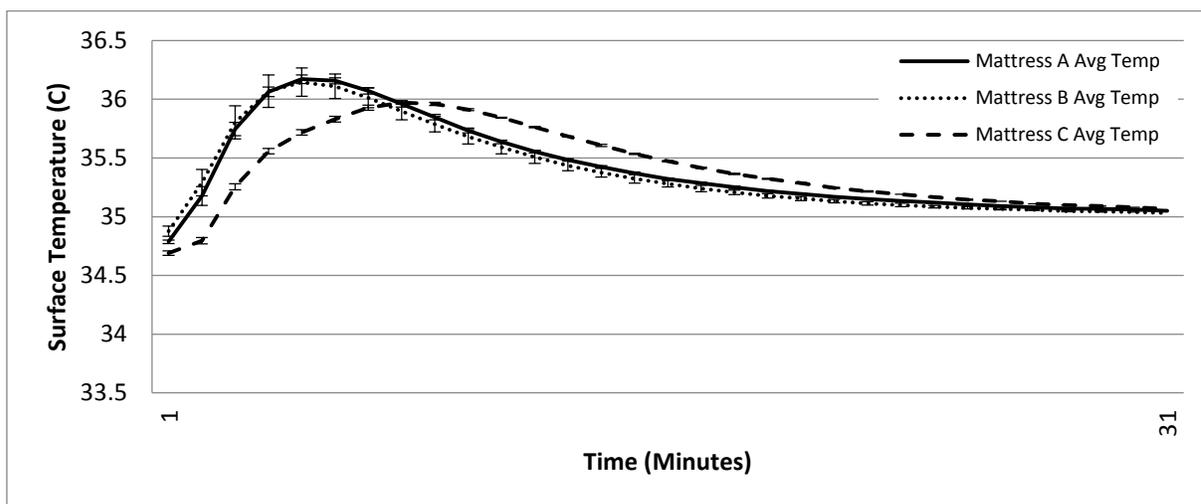
Mattress C has a slightly lower initial surface temperature seen in the first minute of the experiment and a lower peak surface temperature than Mattress A or Mattress B. The test device's surface temperature immediately decreases from the  $35^{\circ}\text{C}$  temperature setpoint upon contact with the mattress as shown in Figure 23. The initial error bars from Figure 23 show

that all three mattresses show significant differences in initial surface temperature. The differences in initial surface temperature are related to the materials used at the surface of the mattress rather than the overall mattress construction. While the initial surface temperatures of Mattresses A and B are significantly different, the surface temperature profiles through the first 60 minutes of the experiment are nearly identical. Mattress C, however, exhibited a delayed response to increase the surface temperature of the ST2-XL.

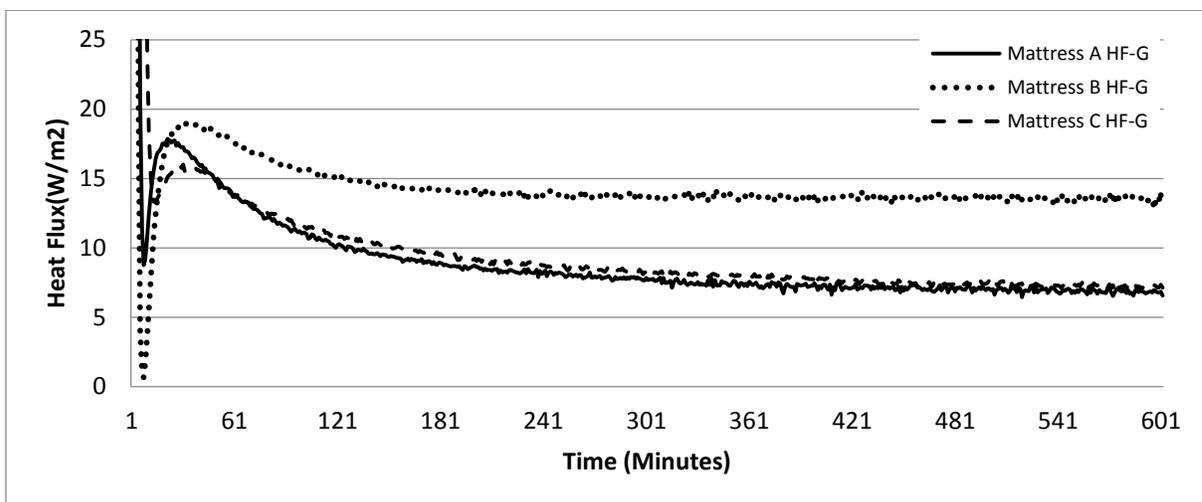
Figure 23 also shows that after about 30 minutes the surface temperature of the test device is 35°C, as it should be. These initial 30 minutes were captured by some of their characteristics such as initial lowest temperature, peak temperature and time-to-peak temperature to analyze this initial 30 minute short term phase for differences between the mattresses. These average values for each condition on each mattress are shown in Table 7.

To characterize the shape and steady state values of the thermal resistance curves, a curve fit was performed. As seen in Figure 24 and Figure 25, the irregularity of the initial 30 minutes of the experiments caused by the device stabilizing would be difficult to characterize with a curve fit. For this reason, the first 30 minutes of the experiment were omitted for the following data analysis of Tau and the steady state Reff. The time constant of the line produced by MATLAB's curve fitting tool describes how long it takes for the mattress to reach a thermal resistance steady state. The one-way ANOVA of Steady State Reff in Figure 26 showed that the ST2-XL and test method shows significant differences between Mattress B to Mattresses A and C. Mattress B shows significantly lower value in steady state thermal resistance compared to Mattresses A and C at each temperature. The one-way ANOVA of  $\tau$

(Time Constant) in Figure 27 showed that the ST2-XL and test method shows significant differences between all three mattresses at each ambient temperature. Mattress B has the lowest  $\tau$  value and Mattress C has the highest  $\tau$  value.



*Figure 23 – Average Surface Temperature of ST2-XL on Each Mattress at 20°C Ambient Temperature over the First 30 Minutes of the Experiment. Mattress C (dashed line) has a delayed response to an increase in temperature compared to Mattress A (solid line) and Mattress B (dotted line).*



*Figure 24 – Average Heat Flux Generated of ST2-XL on Each Mattress at 20°C Ambient Temperature for the Duration of the Experiment. Mattress B (dotted line) requires a significantly higher heat flux to maintain a 35°C test plate surface temperature after the first 30 minutes and for the remainder of the experiment than Mattress A (solid line) or Mattress C (dashed line).*

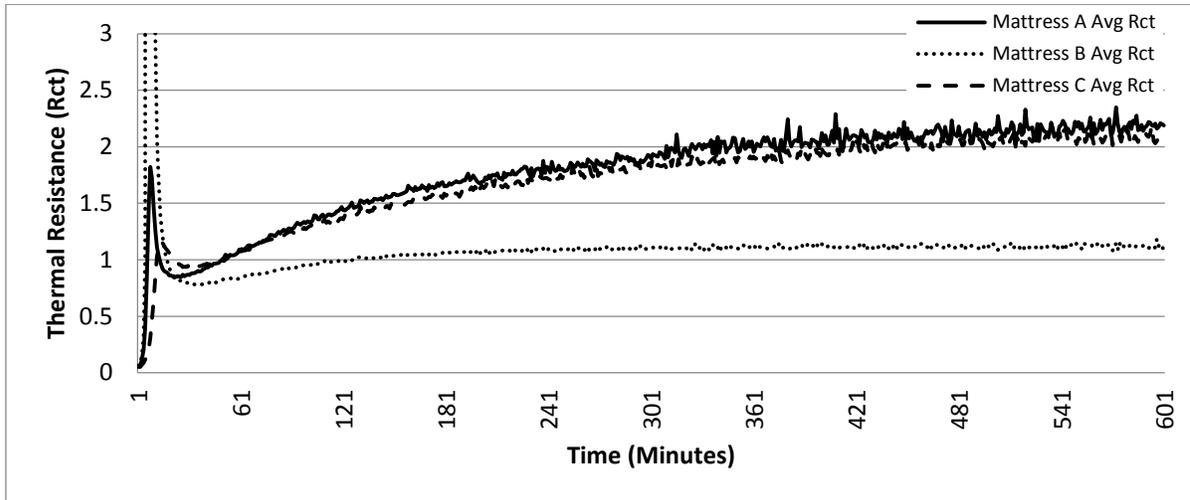
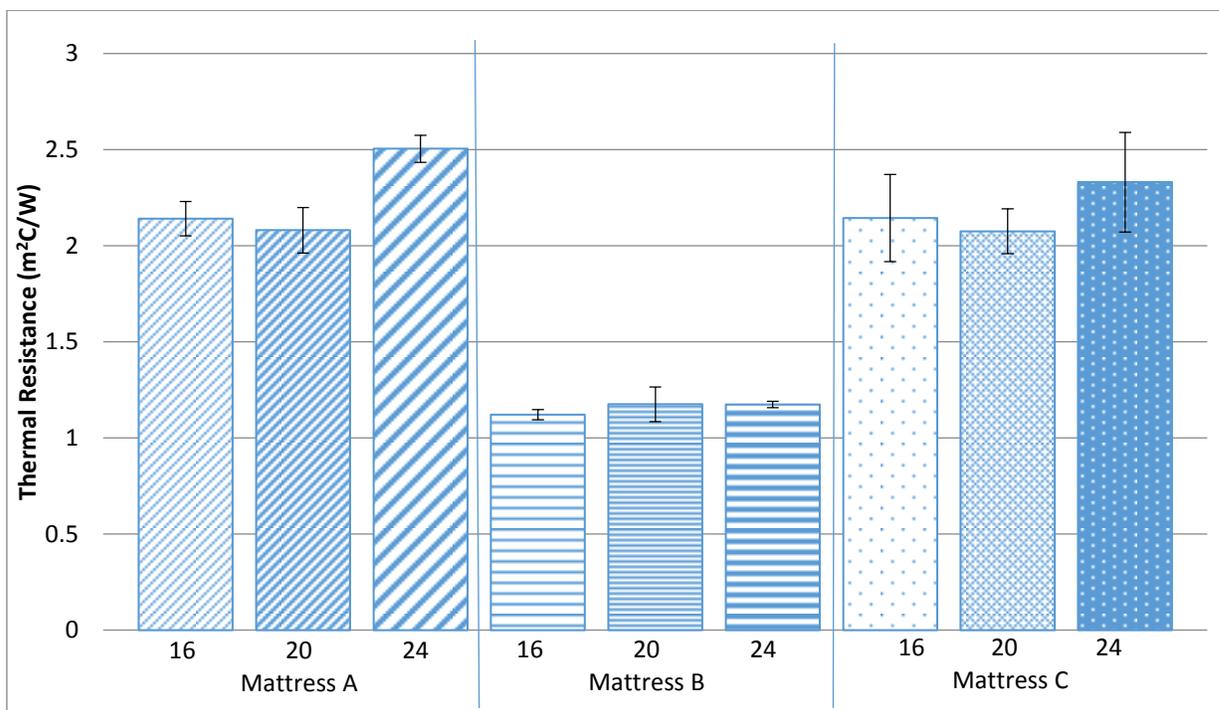
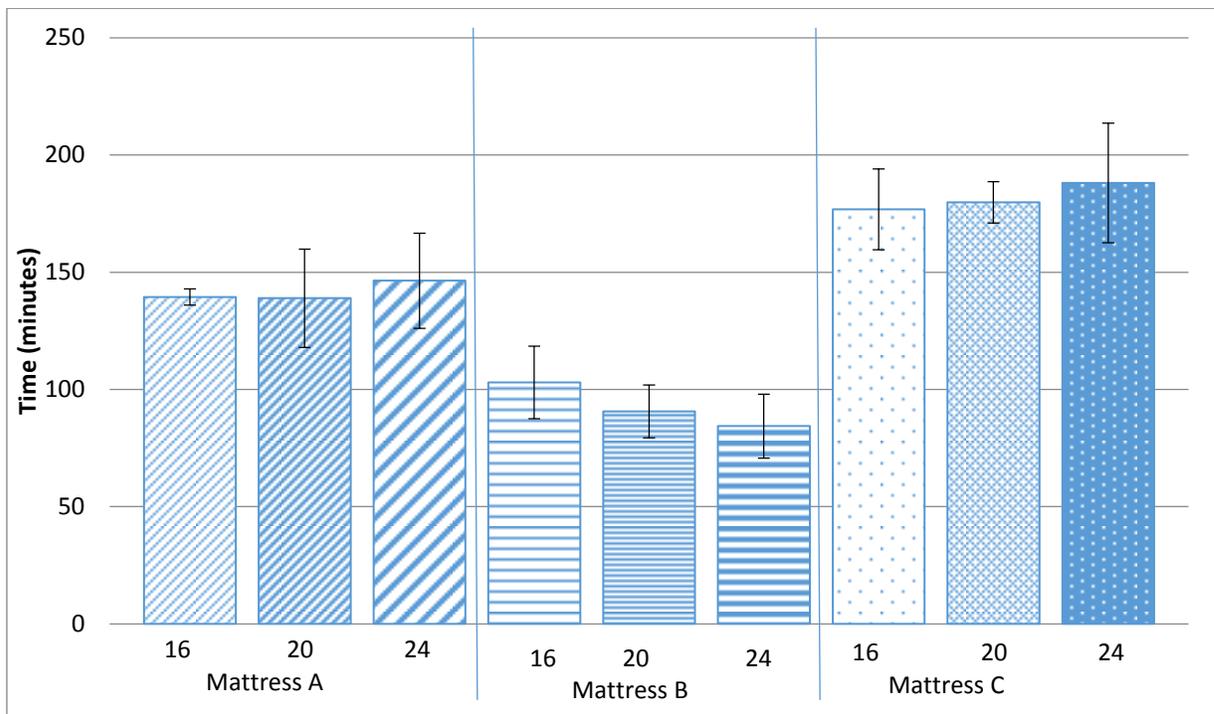


Figure 25 – Average Thermal Resistance ( $R_{eff}$ ) of ST2-XL on Each Mattress at 20°C Ambient Temperature for the Duration of the Experiment. Mattress B (dotted line) has a lower average thermal resistance than Mattress A (solid line) and Mattress C (dashed line) after the first 30 minutes and for the remainder of the experiment.



*Figure 26 – Average Steady State Reff for Each Mattress on ST2-XL at 16°C (light shade), 20°C (medium shade), and 24°C (dark shade) from Curve Fitting with Standard Deviation Error Bars. Mattress B (horizontal stripes) has a significantly lower Reff value at each ambient temperature than Mattress A (diagonal stripes) and Mattress C (dotted) which share similar values.*



*Figure 27 – Average  $\tau$  (Time Constant) for Each Mattress on ST2-XL at 16°C (light shade), 20°C (medium shade), and 24°C (dark shade) from Curve Fitting with Standard Deviation Error Bars. All three mattresses have significantly different values from one another at the three ambient temperatures. Mattress B (horizontal stripes) has the lowest  $\tau$  value and Mattress C (dotted) has the highest  $\tau$  value.*

*Table 7 - Average initial surface temperature, peak surface temperature, and time to peak surface temperature for each mattress at 20°C using Thermal Seat Tester. Mattress C has a significantly lower initial surface temperature and peak surface temperature, and higher time to peak surface temperature than Mattresses B and C.*

Mattress:	Initial Surface Temperature (°C)	Peak Surface Temperature (°C)	Time to Peak Surface Temperature (minutes)
A	34.79	36.17	5.00
B	34.88	36.15	5.00
C	34.69	35.97	8.00

### 3.4 Discussion

Figure 23 demonstrated a difference between the mattresses in regards to initial peak surface temperature of the test device. The peak was a result of the initial decrease from the temperature setpoint of 35°C on initial contact with the mattress. This cooling effect occurs because the surface temperature of the mattress is lower than 35°C and the surface temperature is cooled through conduction. When the test device sensed/measured that the temperature had been lowered from the setpoint, the device increased the heat flux generated to attain this temperature setpoint. This large increase in heat flux caused the device to overshoot the target temperature setpoint and create the peak in the graph. As a result, the

device then lowers the heat flux to reach the initial surface temperature setpoint after around 30 minutes. The average heat flux generated for each mattress during experimentation is shown in Figure 24. Figure 23 illustrates that Mattresses A and B have near identical curves and peaks of surface temperature in the first 30 minutes. Mattress C has a lower peak surface temperature and it more time was required for this mattress to reach its peak than the other two mattresses. As the test device hasn't changed, these differences may be ascribed to differences between the mattresses. This can be explained by the PCMs in Mattress C acting to absorb more heat than the sensible heat storage materials while increasing temperature at a reduced rate until all of the PCMs have transformed into the liquid state [52]. The error bars at the peaks on Figure 24 demonstrated that Mattress C had a significantly lower peak surface temperature than Mattresses A and B.

There are two important aspects of the heat flux generated graph (Figure 24) to consider: the initial local minimum within the first 30 minutes and the steady decrease for the remainder of the experiment. The steep initial decrease was a result a higher device surface temperature than the temperature setpoint of 35°C. While the peak surface temperature of Mattresses A and B were nearly identical, the local minimum in heat flux for the Mattress B curve almost reaches 0 W/m<sup>2</sup> while the Mattress A curve did not drop as low. This demonstrates that the materials used at the surface of Mattress B have a higher resistance to heat flow than the Mattress A. This conclusion is further supported by the thermal resistance graph in Figure 25 which is a close inverse of the heat flux generated graph. As a contrast, however, mattress B has a much lower thermal resistance than Mattress A or Mattress C after

the initial 30 minutes and for the remainder of the experiment. This means that the test device requires less power to maintain the 35°C plate temperature for Mattress A and Mattress C which have higher insulation than for Mattress B which has a lower insulation and thus requires a higher heat flux. These data further suggest that the test device is capable of detecting significant differences in mattress structure in the short term (superficial layer effects) and the longer term (deeper mattress layer effects).

The longer term steady state measurements and estimates were likely mostly influenced by the density and construction of the mattress. Mattress B is an innerspring mattress which allows air to occupy more of the space within the mattress than the foam mattresses. Air has a lower conductivity than the polymers in the mattress. The near stagnant air held in the foam mattresses act as good insulators, while the circulation of the air within the innerspring mattress reduces insulation through convection. The one-way ANOVA test of Tau shown in Figure 27 also shows significant differences between all three mattresses. It is suspected that the density of the mattresses also plays a large factor in the differences seen in these mattresses. The lower density of Mattress B (ref. Table 6) allows for the thermal resistance to reach its asymptote for steady state before the more dense foam mattresses.

Performing this experiment at three different ambient temperatures was necessary to determine if the results or data trends remained consistent at each ambient condition. Figure 26 shows the results for steady state thermal resistance at each ambient temperature and Figure 27 shows the results for the Tau time constant at each ambient temperature. At each ambient temperature, Mattress B maintains the lowest steady state  $R_{eff}$  and Tau time

constant. Mattress A and Mattress B have similar steady state  $R_{eff}$  values at each temperature and have significantly different Tau time constants at each temperature. The three experimental ambient temperatures continue to show similar trends for both the Tau time constant and the steady state thermal resistance. This result is desirable such that the test method can be used at different temperatures for a given application and yield similar data trends. The steady state  $R_{eff}$  value provides a representation of the thermal comfort that a human might perceive in the later hours of the night after remaining in the same location. For example, the low thermal resistance of Mattress B might be perceived as cooler by a human subject than Mattress A and Mattress C which have higher thermal resistance values. The Tau time constant value explains how long it takes to reach the steady state  $R_{eff}$  value. Thus, the Tau value describes how long it takes the mattress to have its highest thermal resistance which provides further insight into the thermal comfort that might be perceived by a human subject after a certain amount of time on the mattress. For example, a lower tau value could represent a mattress that heats up to its maximum temperature the fastest.

In Equation 21,  $R_{eff}$  is used instead of the standard  $R_{ct}$ , because the actual heat loss from the hot plate may be limited by an internal mattress temperature that doesn't necessarily equal the air temperature. As the test device transfers heat onto the mattress, the mattress heats up below the test plate and the distance between the 35°C plate temperature and the 20°C area of the mattress increases making it difficult to characterize as mattresses are typically very thick materials.

A limitation of this experiment is that this current test method does not begin on initial contact with the mattress. In the current test method, the experiment begins upon starting it on the software and then the test plate is placed on the mattress about 3 seconds after. Although this is not of huge concern, having the test plate touch the mattress and the test beginning simultaneously would be preferable to reduce human error in this experiment because it is not guaranteed that the test plate will be placed on the mattress at the exact same time for every experiment. This factor could potentially result in inconsistent data for the first minutes of the experiment. Additional testing is necessary to validate the repeatability of this experiment as three repetitions for each mattress at each condition does not seem adequate.

### **3.5 Conclusions**

It has been demonstrated that the thermal seat tester and the described test method can detect repeatable differences between the thermal properties of these three mattresses. The initial surface temperature and the peak surface temperature of the device demonstrate its ability to detect thermal differences in the short term, while curve fitting the Reff measurements using MATLAB® reveal thermal differences in the long term. The short term differences provide evidence to the thermal sensation that would be experienced by a human subject during the first 30 minutes of lying on the mattress. Long term thermal differences give evidence of the thermal sensation that would be experienced by a human subject after lying on the mattress for over 30 minutes. These results would be more meaningful if a human subject could describe the same thermal differences that have been presented. For

this reason, future steps in this research are to determine whether these differences can be detected by humans through subjective thermal comfort evaluations.

## **CHAPTER 4: A Comparison of Mattresses Using a Thermal Manikin:**

### **4.1 Introduction**

The measurement of heat transfer properties is not a new concept to the textile industry per se, particularly not the clothing industry. Two common instruments used to determine these properties in clothing and textile systems are the sweating guarded hotplate and the (sweating) thermal manikin. These two measurement systems operate similarly, but differ in strengths and weaknesses. The sweating guarded hot plate is described in international standards, such as ASTM F1868 and ISO 11092 [30]. The thermal manikin is described in ASTM Standards F1930 and F2370 as well as ISO 15831. In these standards, measurement systems operate in a mode that sets a temperature difference and measures the heat flux through the fabric system. Alternatively, these methods could be set to a mode where a constant heat flux is provided and the resulting temperature difference is measured. The sweating guarded hotplate is specifically geared towards accurately measuring the fabric properties, but its limitation is that it does not introduce the fit or drape that might be associated with the fabric when it is worn by a human [30]. The thermal manikin is more useful for analyzing thermal properties of the clothing garments and does introduce the fit and drape that might be experienced by a human.

While both of these systems could be useful for analyzing the thermal properties of mattresses, cushions, or other bedding materials, the present study will focus on the thermal manikin system, as this system provides a better interpretation of the human body and its shape will be impacted by the mattress. The usage of thermal manikins to study comfort goes back nearly 70 years [41]. Many types of manikins have been developed over this period including manikins that are capable of sweating at different rates. For the purpose of a mattress study, a segmented thermal manikin capable of describing responses to the mattress at localized regions is important to have because the different areas of the body will have varying levels of contact and pressure onto the mattress. As sweat rates are generally low in comfortable sleep environments, the experiments described here have focused first on the evaluation of dry heat loss and sweat production was not incorporated in these experiments.

There are already standard protocols for estimating the thermal characteristics and insulation of clothing using thermal manikins as seen in ASTM F1291 and ISO 7920. However, there are no current standard protocols to the knowledge of the author for assessing the thermal characteristics of mattresses using thermal manikins.

It is obvious that the effectiveness of heat loss through conduction and convection will vary depending on the amount of coverage provided by the bedding system. Thus, it is important to note the differences in covered manikin trials versus naked manikin trials. In a study by Pan[7], different air supply temperatures were applied to a female naked sleeping thermal manikin on a mattress and the heat loss from the body was measured for different air velocities. This manikin was set to have a mean skin temperature of 31°C in the hands and

feet, and 35°C for the remaining areas to give a whole body mean skin temperature of 34.6°C. The area coverage of this manikin is suggested to be 23.3% provided by the mattress alone [7]. This study found that higher percentage coverage by the bedding will increase the differences of the bedding materials.

A similar thermal manikin study which used the same three bedding materials as the experiment above, but also included two different mattress types found that mattress type had a significant effect on the total insulation values ( $I_T$ ) of the bedding systems [16]. The effect that the mattresses had on the total insulation values increased as the area covered ( $A_c$ ) by the bedding increased. This difference in  $I_T$  between the mattresses was also shown to increase as the insulation of the sleepwear increased even when no bedding is used. The parameters from this experiment were calculated from at least 30 steady-state points of data, but the time to reach steady state for each test was not provided.

This paper reports results of an experimental study comparing the thermal properties of three different mattresses using a segmented thermal manikin in an environmental chamber at 20°C. The comparison will seek to find objective thermal differences in the mattresses in both the short-term and long-term by analyzing the surface temperature, heat flux generated, and thermal resistance of the mattresses.

## 4.2 Experimental Method and Materials

### 4.2.1 Materials

The bedding system consisted of an adjustable mattress frame, a box spring, a mattress, a cotton fitted sheet, and a duvet. The bedding system setup remained consistent throughout the series of experiments other than changing out the mattresses. The mattresses used for this study were all twin size mattresses. The specifications for the three mattresses (A, B, and C) are shown in Table 8 below. Mattress A was a polyurethane (PU) foam mattress, Mattress B was an innerspring mattress, and Mattress C was a PU foam mattress enhanced with phase change materials (PCMs).

*Table 8 – Mattress Specifications for Manikin Testing*

Experimental Name:	Mattress A	Mattress B	Mattress C
Mattress Construction:	PU Foam	Innerspring	PU Foam with PCMs
Area Dimensions (cm): (L x W)	185 x 94	202 x 97	193 x 91
Thickness (cm):	25	20	31
Weight (kg):	18.15	14.95	27.20
Density (g/cm <sup>3</sup> ):	0.0417	0.0381	0.0499

The measurement device ('test device') used for the present study was a segmented thermal manikin developed by Thermetrics in Seattle, Washington. A distributed heater,

distributed temperature sensor, and distributed heat flux sensor are embedded within each of the 34 individual segments of the manikin to obtain accurate measurements. In the experiments conducted here, all of the segments were temperature controlled and set to 35°C to represent the temperature of human skin. The hands, feet, and guard segments (6 total segments) were omitted from the analysis due to lack of contact with the mattress. The manikin was broken up into Back and Front segments for ease of analysis with the individual segments providing area weighted contributions to the Front or Back segments. The experiments yielded three important variables through the control software which were heat flux generated ( $\text{W}/\text{m}^2$ ), test plate temperature ( $^{\circ}\text{C}$ ), and thermal resistance ( $^{\circ}\text{Cm}^2/\text{W}$ ). The calculation performed by the control software to obtain the thermal resistance ( $R_{\text{eff}}$ ) is shown in Equation 20.

$$\text{Eq. 20 Thermal Resistance, } (m^2C)/W: R_{\text{eff}} = \frac{T_s - T_a}{Q/A}$$

Where  $T_s$  = Skin Temperature ( $^{\circ}\text{C}$ ),  $T_a$  = Ambient Temperature ( $^{\circ}\text{C}$ ), and  $Q/A$  = Area Weighted Heat Flux ( $\text{W}/\text{m}^2$ ).

In Equation 1,  $R_{\text{eff}}$  is used instead of the standard  $R_{\text{ct}}$ , because the actual heat loss from the hot plate may be limited by an internal mattress temperature that doesn't necessarily equal the air temperature.

#### ***4.2.2 Experimental Procedure***

The mattress frame, box spring, and mattress were placed in the middle of the environmental testing chamber and a cotton fitted sheet was secured to the mattress being

tested. The chamber was 20°C, 65% RH, and had a wind speed of 0.3m/s. The sheet was adjusted such that there were no wrinkles and the test region had a smooth surface. Before testing, the testing materials were conditioned to the desired testing environment for at least 20 hours and the segments of the manikin were preheated to 35°C. The test was initialized using the ThermDAC 8 control software and the manikin was immediately and carefully placed on the middle of the mattress with no regions of overhang in the supine position. The duvet was then placed over the manikin and tucked just below the chin of the manikin to reach approximately 94.1% area cover of the manikin. The experiment was then allowed to run undisturbed in the chamber for at least 5 hours. When the test time was completed, the test was ended on the ThermDAC 8 control software and the manikin was removed from the mattress.

#### ***4.2.3 Data Analysis***

After completing the experiments, the data files were transferred to begin data analysis. Graphs of the important measured variables (Heat Flux Generated, Surface Temperature, and Thermal Resistance (Reff)) versus Time were created in to obtain a visual understanding of the data trends in the experiments.

While the graphs provided sufficient understanding of the data in the initial hours of the experiments, they could not provide complete steady state values because of the length of time required to reach this state. For this reason, the curve fitting tool in MatLab R2014b by MathWorks® was used to obtain an estimate of the steady state Reff values and the time

required to reach the estimated steady state. Due to discontinuities found in the initial thirty minutes (discussed later), the data in the initial thirty minutes was omitted from the data analysis using the curve fitting tool to obtain curves with a greater adjusted R-squared value. The equation used to calculate the curve fit is shown by Equation 21.

$$Eq\ 21: y = f(x); \text{ where } x = a * (1 - ce^{-x/\tau})$$

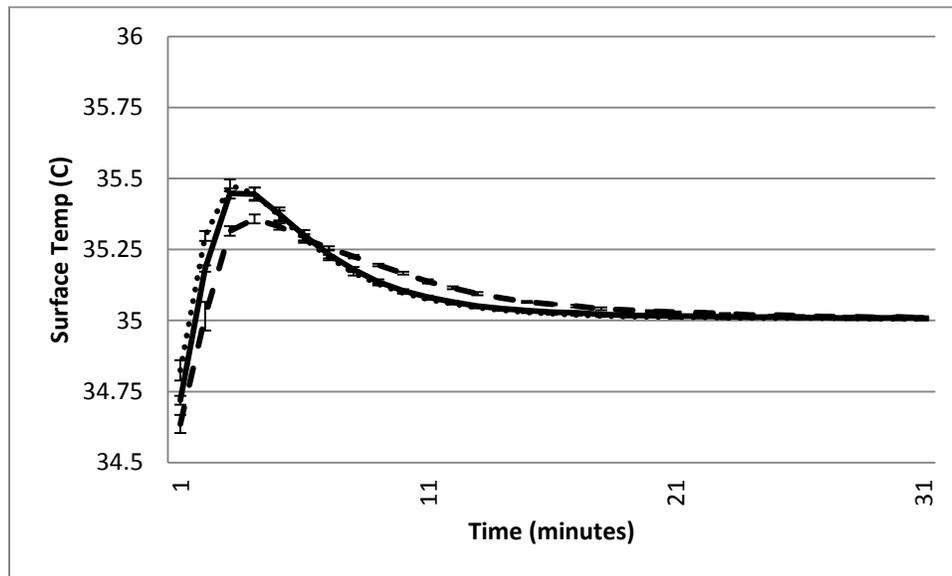
Where a = Steady State Reff ( $^{\circ}\text{C}\cdot\text{m}^2/\text{W}$ ),  $\tau$  = Time Constant Indicating Time to Reach Steady State Reff (Minutes).

The statistical significance of the notable data trends obtained from both the graphs in and the curve fitting tool were calculated by using one-way ANOVA tests in JMP Pro 11 by SAS.

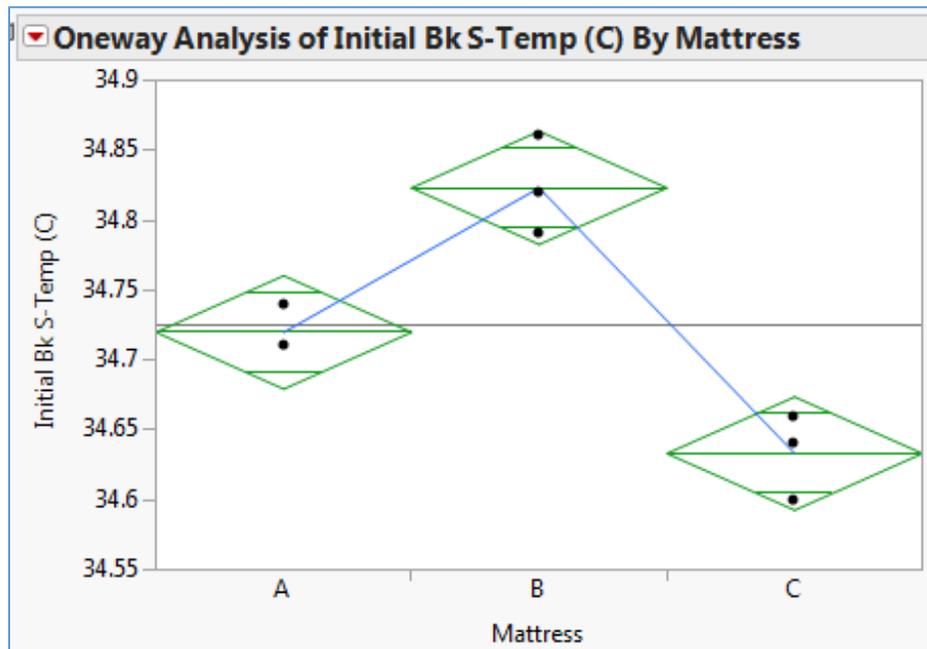
### 4.3 Results

Mattress C has a slightly lower initial surface temperature seen in the first minute of the experiment and a lower peak surface temperature than Mattress A or Mattress B. The manikins' back surface temperature immediately decreases from the  $35^{\circ}\text{C}$  temperature setpoint upon contact with the mattress as shown in Figure 28. The one-way ANOVA test in Figure 29 shows that all three mattresses show significant differences in initial back surface temperature. While the initial back surface temperatures of Mattresses A and B are significantly different, the surface temperature profiles through the first 60 minutes of the experiment are nearly identical. Mattress C, however, exhibited a delayed response to increase the surface temperature of the thermal manikin. This is also shown in Figure 30

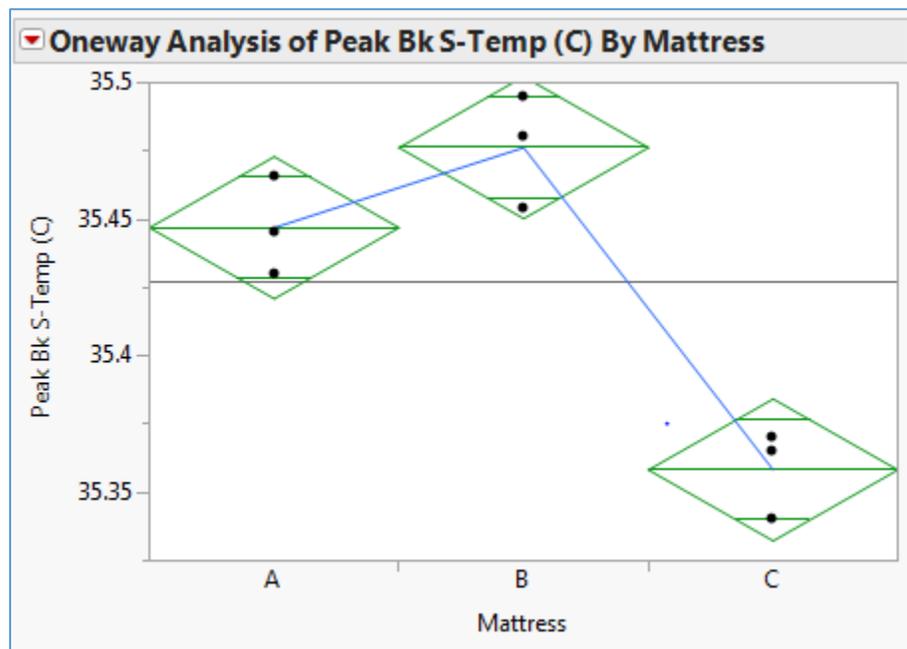
where the peak back surface temperature of the manikin on Mattress C was significantly lower than on Mattresses A and B. These differences in surface temperature are not seen on the front of the manikin where the duvet is kept constant as shown in Figure 31.



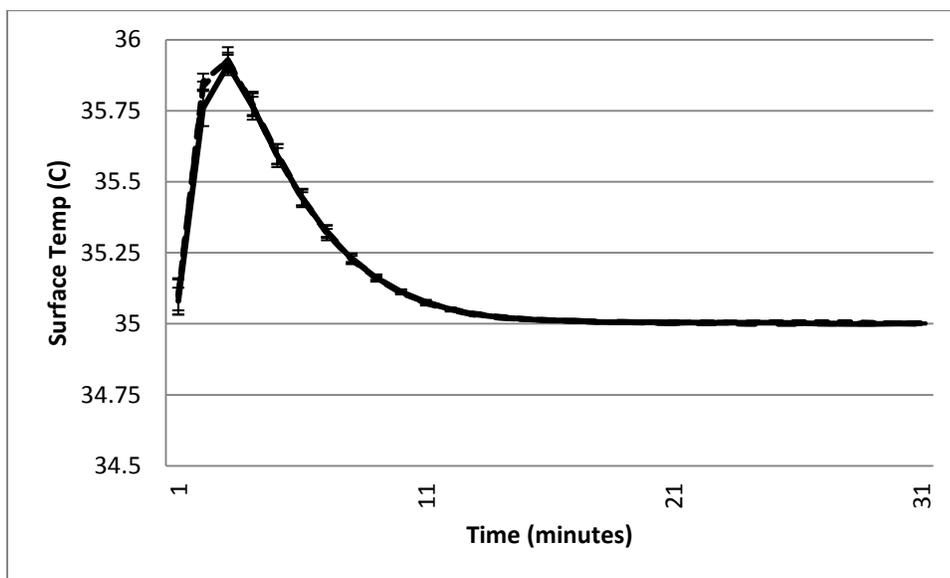
*Figure 28 – Average Surface Temperature of Thermal Manikin Back on Each Mattress at 20°C Ambient Temperature Over the First 30 Minutes of the Experiment. Mattress C (dashed line) has a delayed response to an increase in temperature compared to Mattress A (solid line) and Mattress B (dotted line).*



*Figure 29 – One-Way ANOVA Test on the Initial Surface Temperature of the Thermal Manikin Back. Mattress C has a lower initial surface temperature than Mattress A and Mattress B.*



*Figure 30 – One-Way ANOVA Test on the Peak Surface Temperature of the Thermal Manikin Back. Mattress C has a lower peak surface temperature than Mattress A and Mattress B.*



*Figure 31 – Average Surface Temperature of Thermal Manikin Front on Each Mattress at 20°C Ambient Temperature Over the First 30 Minutes of the Experiment. All three mattresses behave the same.*

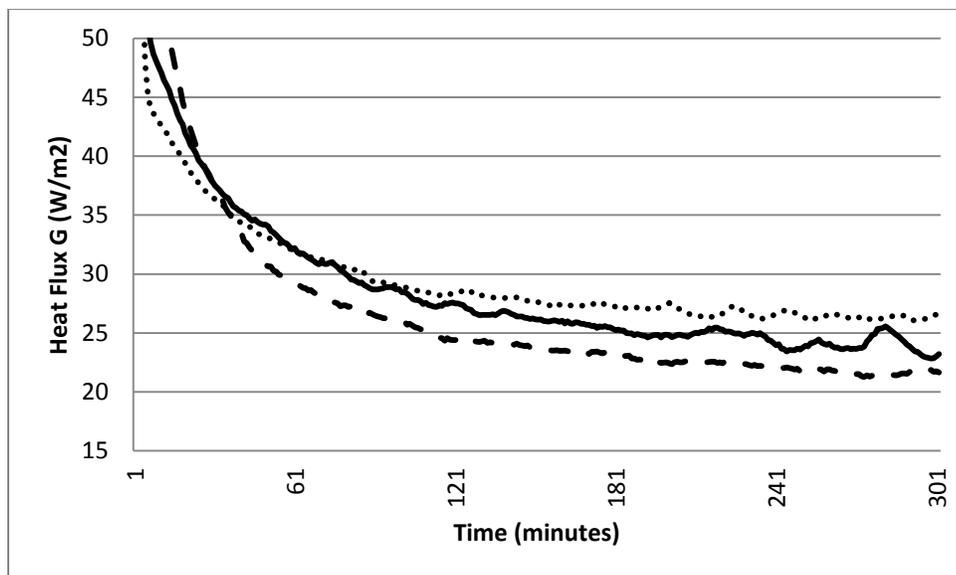
Figure 28 also shows that after about 30 minutes the surface temperature of the test device is 35°C, as it should be. These initial 30 minutes were captured by some of their characteristics such as initial lowest temperature, peak temperature and time-to-peak temperature to analyze this initial 30 minute short term phase for differences between the mattresses. These average values on each mattress are shown in Table 9.

*Table 9 – Average initial surface temperature, peak surface temperature, and time to peak surface temperature for each mattress at 20°C using thermal manikin. Mattress C has a significantly lower initial surface temperature, peak surface temperature, and time to peak surface temperature than Mattress B and Mattress C.*

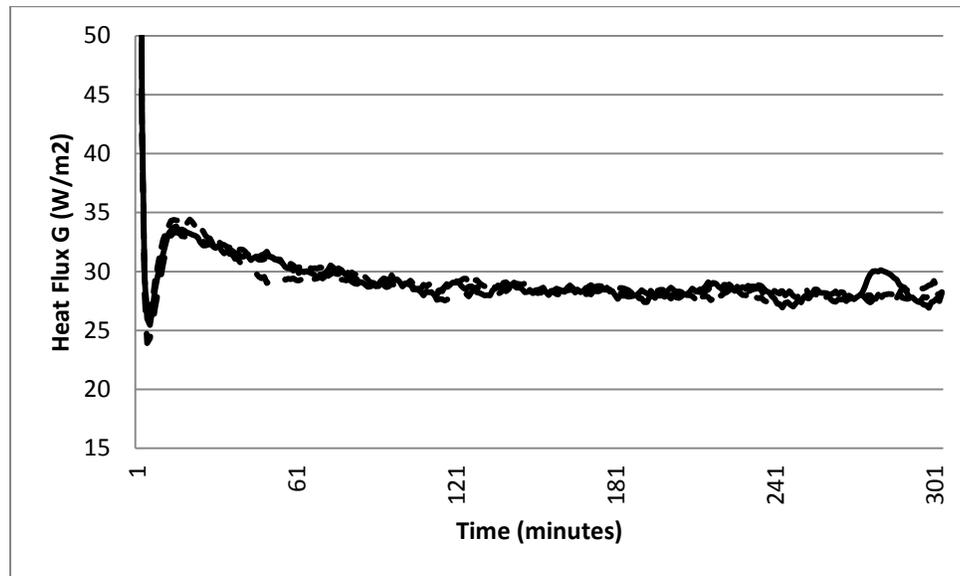
Mattress:	Initial Back Surface Temperature (°C)	Peak Back Surface Temperature (°C)	Time to Peak Back Surface Temperature (minutes)
A	34.72	35.44	3.33
B	34.82	35.47	3
C	34.63	35.35	4

Figure 32 and Figure 33 show the heat flux generated by the manikin in the back and front regions respectively. The heat flux generated by the back region of the manikin shows differences between mattresses, while the front region of the manikin behaves similarly regardless of mattress. The manikin's back generates the least heat flux on Mattress C after less than 60 minutes on the mattress. The shapes of the graphs generated by the back of the manikin are noticeably different from the graphs generated by the front of the manikin. In Figure 32, the heat flux generated decreases rapidly for 30 minutes then slowly decreases for the remainder of the experiment. In Figure 33, the heat flux generated decreases rapidly for 5

minutes, followed by rapid increase for 10 minutes before slowly decreasing for the remainder of the experiment.

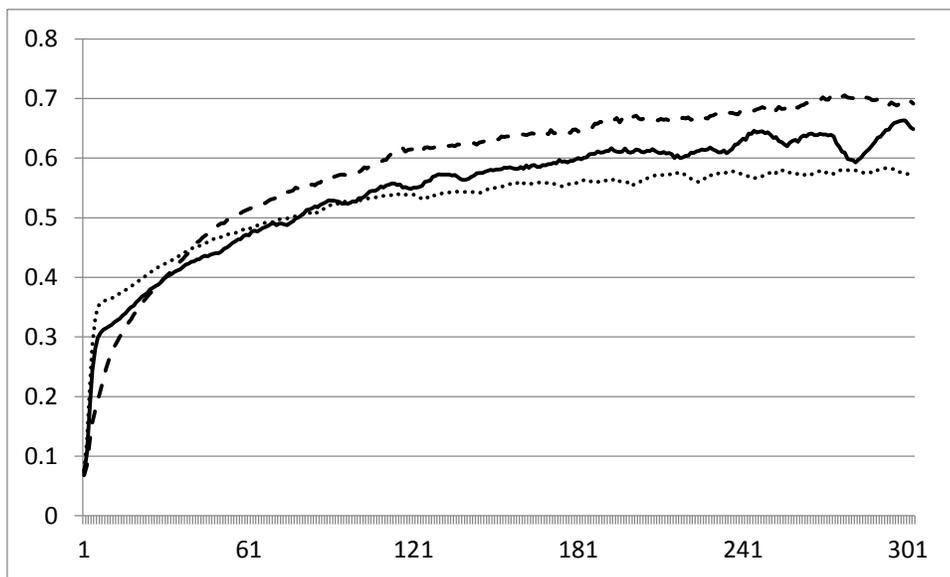


*Figure 32 – Average Heat Flux Generated of Thermal Manikin Back on Each Mattress at 20°C Ambient Temperature During the Experiment. Mattress C (dashed line) requires the least heat flux to maintain 35°C compared to Mattress A (solid line) and Mattress B (dotted line).*

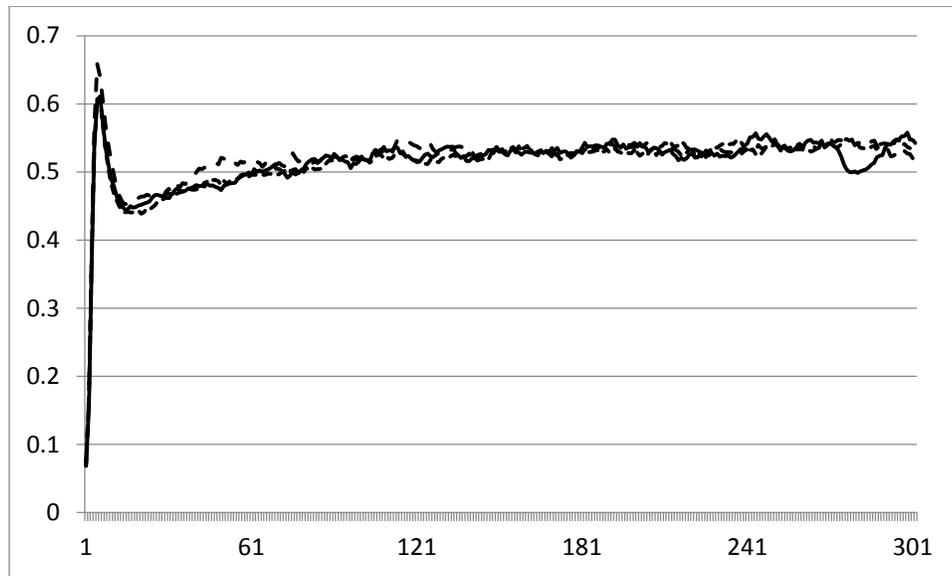


*Figure 33 – Average Heat Flux Generated of Thermal Manikin Front on Each Mattress at 20°C Ambient Temperature During the Experiment. The manikin heat flux at the front regions behaves similarly on all three mattresses.*

These shape differences between the front and back regions found in the heat flux generated result in different shapes in the thermal resistance graphs. The thermal resistance on the back of the manikin, in Figure 34, produced graphs that increased rapidly for 30 minutes then continued to slowly increase for the remainder of the experiment. Here, Mattress C has the highest ending thermal resistance while Mattress B has the lowest. The thermal resistance of the front of the manikin, as seen in Figure 35, increases quickly for 5 minutes, followed by a quick decrease for 10 minutes before slowly increasing for the remainder of the experiment. None of the mattresses showed significant difference from one another in the thermal resistance at the front regions of the manikin.



*Figure 34 – Average Reff of Thermal Manikin Back on Each Mattress at 20°C Ambient Temperature During the Experiment. Mattress C (dashed line) has the highest Reff compared to Mattress A (solid line) and Mattress B (dotted line).*



*Figure 35 – Average Reff of Thermal Manikin Front on Each Mattress at 20°C Ambient Temperature During the Experiment. The manikin Reff at the front regions behaves similarly on all three mattresses.*

To characterize the shape and steady state values of the thermal resistance curve for the back of the manikin, a curve fit was performed. A curve fit was not necessary for the front of the manikin since the graphs in Figure 35 showed little difference between mattresses. As seen in Figure 28, the fluctuation of temperature in the initial 30 minutes of the experiments caused by the device stabilizing would be difficult to characterize with a curve fit. For this reason, the first 30 minutes of the experiment were omitted for the following data analysis of Tau and the steady state Reff. The time constant of the line produced by MATLAB's curve fitting tool describes how long it takes for the mattress to reach a thermal resistance steady state. The one-way ANOVA of Steady State Reff in Figure

36 showed that the thermal manikin and test method shows significant differences between Mattress B and Mattress C. Mattress B shows significantly lower value in steady state thermal resistance compared to Mattress C. The one-way ANOVA of  $\tau$  (Time Constant) in Figure 37 showed that the thermal manikin and test method shows significant differences between Mattress A and Mattress B. Mattress B has the lowest  $\tau$  value and Mattress A has the highest  $\tau$  value.

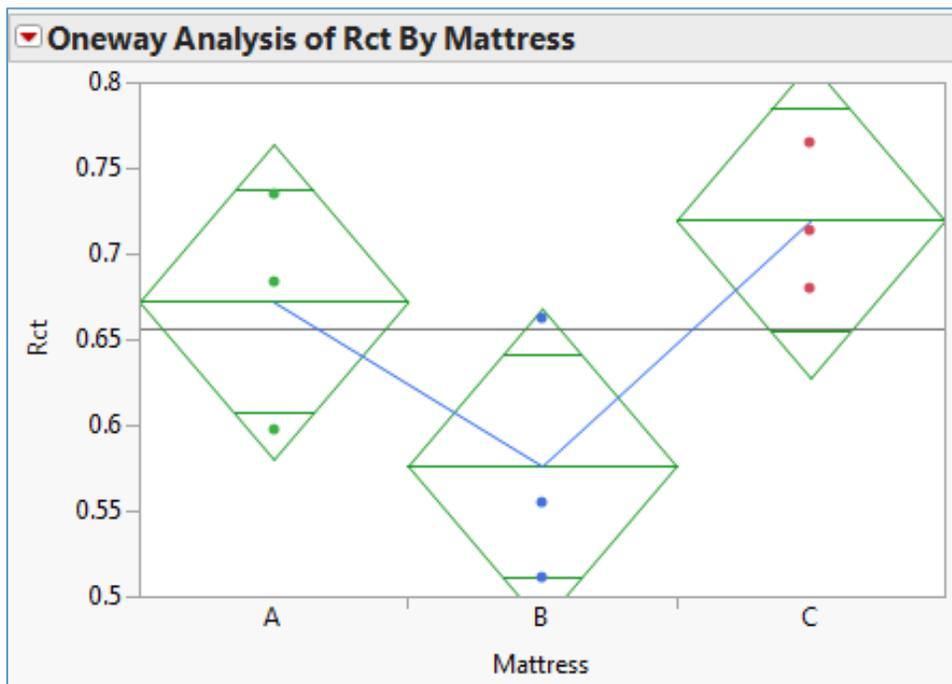
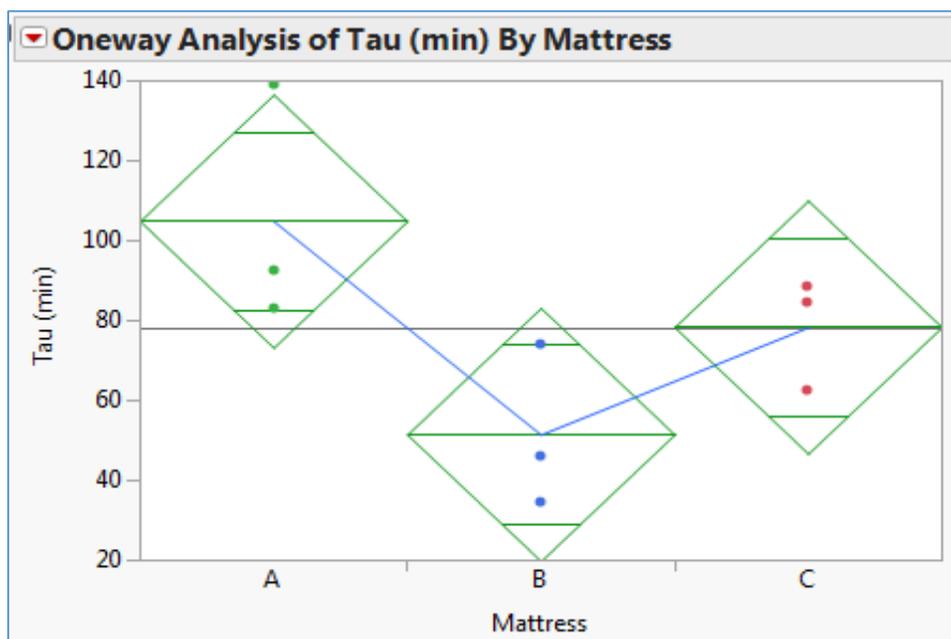


Figure 36 – One-Way ANOVA Test of Steady State Reff from Curve Fitting for Each Mattress on Thermal Manikin Back. Mattress B has a lower steady state Reff value than Mattress A and Mattress C.



*Figure 37 – One-Way ANOVA Test of Tau Time Constant from Curve Fitting for Each Mattress on Thermal Manikin Back. Mattress B has a lower value than Mattress A and Mattress C.*

#### 4.4 Discussion

Figure 28 demonstrated differences between the mattresses in regards to the initial temperature and peak surface temperature at the back of the manikin. The peak was a result of a combination of the initial decrease from the temperature setpoint of 35°C on initial contact with the mattress and the high insulation provided by the mattress/bedding. This cooling effect occurs because the surface temperature of the mattress is lower than 35°C and the surface temperature is cooled through conduction. The differences in initial back surface temperature are related to the materials used at the surface of the mattress rather than the

overall mattress construction. When the test device sensed/measured that the temperature had been lowered from the setpoint, the device increased the heat flux generated to attain this temperature setpoint. This heat flux, as seen in Figure 34, caused the device to overshoot the target temperature setpoint and create the peak in the graph. As a result, the device then lowers the heat flux to reach the initial surface temperature setpoint after around 30 minutes. The back of the manikin (in contact with mattress) responded differently than the front (in contact with duvet) for two reasons: 1) the PID controller of the manikin is programmed to respond steadily to changes in temperature which created a graph that would not overshoot the necessary heat flux caused by the cooling effect between the mattress and manikin's back and 2) there are assumed to be areas on the backside of the manikin that are not in full contact with the mattress which could impact the responsiveness of the segments on the manikin. Figure 28 illustrates that Mattresses A and B have near identical curves and peaks of surface temperature in the first 30 minutes. Mattress C has a lower peak surface temperature and it more time was required for this mattress to reach its peak than the other two mattresses. As the test device hasn't changed, these differences may be ascribed to differences between the mattresses. This can be explained by the PCMs in Mattress C acting to absorb more heat and reducing temperature increase until all of the PCM have transformed into the liquid state [48]. The error bars at the peaks on Figure 28 demonstrated that Mattress C had a significantly lower peak surface temperature than Mattresses A and B.

In Figure 32, it is seen that heat flux generated at the back of the manikin is lowest for Mattress B during the initial 30 minutes of the experiment. This demonstrates that the

materials used at the surface of Mattress B have a higher resistance to heat flow than the Mattress A and Mattress C. This conclusion is further backed by the thermal resistance graph of the back of the manikin in Figure 34 which is a close inverse of the heat flux generated graph. As a contrast, however, Mattress B has a lower thermal resistance than Mattress A or Mattress C after the initial 2 hours and for the remainder of the experiment. This thermal resistance can be seen to steadily increase for the remainder of the experiment for each mattress. It continues to steadily increase because the mattresses are storing more heat and this is providing insulation to the back of the manikin. These data further suggest that the test device is capable of detecting differences in mattress structure in the short term (superficial layer effects) and the longer term (deeper mattress layer effects).

The longer term steady state measurements and estimates were likely mostly influenced by the density and construction of the mattress. Mattress B is an innerspring mattress which allows air to occupy more of the space within the mattress than the foam mattresses. Air has a lower conductivity than the polymers in the mattress. The near stagnant air held in the foam mattresses act as good insulators, while the circulation of the air within the innerspring mattress reduces insulation through convection. The one-way ANOVA test of steady state  $R_{eff}$  in Figure 36 showed significant difference between Mattress B and Mattress C. The one-way ANOVA test of response time constants ( $\tau$ ) shown in Figure 37 did not show significant differences between all three mattresses. It is suspected that the density of the mattresses also plays a large factor in the long term differences seen in these mattresses. The lower density of Mattress B (ref. Table 8) allows for the thermal resistance to reach its

asymptote for steady state before the more dense foam mattresses and there is a significant difference between Mattress A and Mattress B.

The steady state  $R_{eff}$  value provides a representation of the thermal comfort that a human might perceive in the later hours of the night after remaining in the same location. For example, the low thermal resistance of Mattress B might be perceived as cooler by a human subject than Mattress A and Mattress C which have higher thermal resistance values. The Tau time constant value explains how long it takes to reach the steady state  $R_{eff}$  value. Thus, the Tau value describes how long it takes the mattress to have its highest thermal resistance which provides further insight into the thermal comfort that might be perceived by a human subject after a certain amount of time on the mattress. For example, a lower Tau value could represent a mattress that heats up to its maximum temperature the fastest.

In Equation 20,  $R_{eff}$  is used instead of the standard  $R_{ct}$ , because the actual heat loss from the hot plate may be limited by an internal mattress temperature that doesn't necessarily equal the air temperature. As the test device transfers heat onto the mattress, the mattress heats up below the manikin and the distance between the 35°C plate temperature and the 20°C area of the mattress increases making it difficult to characterize as mattresses are typically very thick materials.

A limitation of this experiment is that this current test method does not begin on initial contact with the mattress. In the current test method, the experiment begins upon starting it on the software and then the manikin is placed on the mattress about 3 seconds after. Although this is not of huge concern, having the manikin touch the mattress and the test

beginning simultaneously would be preferable to reduce human error in this experiment because it is not guaranteed that the manikin will be placed on the mattress at the exact same time for every experiment. This factor could potentially result in inconsistent data for the first minutes of the experiment. It is also difficult to ensure that the manikin is placed in the exact same position every time it is placed on the mattress due to the arms and legs being mobile during placement. This factor could introduce error into the experiment. The variability of the long term results in Figure 36 and Figure 37 was too high for these measurements to provide meaningful data. Additional testing is necessary to validate the repeatability of this experiment as three repetitions for each mattress does not seem adequate.

#### **4.5 Conclusion**

It has been demonstrated that the thermal manikin and the described test method can detect repeatable differences between the thermal properties of these three mattresses. The initial surface temperature and the peak surface temperature of the device demonstrate its ability to detect thermal differences in the short term, while curve fitting the Reff measurements using MATLAB® reveal thermal differences in the long term from the time constant to reach steady state. The short term differences provide evidence to the thermal sensation that would be experienced by a human subject during the first 30 minutes of lying on the mattress. Long term thermal differences give evidence of the thermal sensation that would be experienced by a human subject after lying on the mattress for over 30 minutes. These results would be more meaningful if a human subject could describe the same thermal

differences that have been presented. For this reason, future steps in this research are to determine whether these differences can be detected by humans through subjective thermal comfort evaluations.

## **CHAPTER 5: Human Comfort Trials Comparing Three Mattresses:**

### **5.1 Introduction**

The two previous chapters have shown that the ST2-XL and segmented thermal manikin test devices can describe the thermal properties of mattresses related to comfort. These objective measurements show how a piece of equipment can describe the thermal properties of a mattress. The ST2-XL test device found repeatable significant differences between three mattresses in both the short term and long term, while the thermal manikin was only able to find repeatable thermal differences in the short term. Human thermal comfort trials on the same three mattresses were of interest to validate the thermal comfort predicted by the test devices. Obtaining both subjective and objective data from test subjects would show whether mattress users could subjectively perceive similar thermal differences between the mattresses and if their body's responded differently to the mattresses.

There have been previous studies performed evaluating the thermal comfort of cushioned materials using human subject thermal comfort perception on both airplane seats [26] and ambulance mattress stretchers [53]. The Hohenstein Institute obtained both objective and subjective data from test subjects while sitting on two different seating constructions. The objective data obtained from the experiment consisted of rectal, skin and

microclimate temperatures, heart rate, sweat loss, sweat uptake of clothes, and oxygen consumption. Subjective heat, moisture, and comfort sensations were obtained for subjective data according to ISO 10551 [24]. The four test subjects were asked to rank their overall climatic seat comfort using a Likert scale ranging from 1 (Very Good) to 4 (Unsatisfactory). Testing conditions for the seat trials were in a climatic chamber similar to the present study with an ambient temperature at 20.5°C, 15% RH, and a wind speed of 0.3 m/s. T-Tests at different levels were used to prove the statistical significant. Findings showed mean relative humidity of microclimate during test subject seat trails shows significant difference between the two airplane seat constructions with the leather/foam construction having a higher mean relative humidity that increases throughout the duration of test while the fabric/spacer knit construction decreases during the experiment. T-tests on water vapor resistance,  $R_e$ , showed that the leather/foam construction had significantly higher values than the fabric/spacer knit construction. A lower  $R_e$  value is desirable as it indicates better breathability. Subjective assessments of the overall climatic comfort of the seats differed significantly as well with average value for fabric/spacer knit seat scoring 2.1 (good) compared to the leather/foam seat scoring 2.6 (unsatisfactory) [26].

A study investigating the thermal comfort of ambulance mattresses also used subjective scales and objective measurements for analysis [53]. In this experiment, one mattress was heated to 35°C and one was not heated electronically with both mattresses using a cotton fitted sheet and a polyester blanket with the same texture and softness [53]. Two separate groups of 30 test subjects lied on each mattress. The Cold Discomfort Scale (CDS),

a subjective judgment scale for assessing thermal comfort. An infrared thermometer was used to measure the finger temperature of the subjects during their time on the mattresses. CDS results showed that subjects had improved thermal comfort on the heated mattresses and a decreased thermal comfort on the standard ambulance mattress. Finger temperature measurements of subjects did not present any significant differences between the two mattresses [53].

The present study has similar and different aspects to these experiments. The guidelines in ISO 10551 were used to assess thermal comfort like the airplane seat experiment instead of the CDS used in the ambulance mattress study. However, unlike the airplane seat experiment, in this study we chose to have multiple subjective thermal comfort assessments during the experiments to show how thermal comfort changes over the course of the experiment. Furthermore, the overall and localized thermal comfort were of interest in this study instead of just overall thermal comfort as done in the airplane seat experiment and ambulance mattress experiment. The airplane seat tests were more related to moisture comfort than thermal comfort. Ambulance mattress tests only took finger temperature measurements. Experiments on mattresses such as this could be improved by taking measurements at more localized positions on the body that are in contact with the material to understand how the body is responding to the material.

This study is part of an ongoing research effort to develop a standardized method for testing the thermal comfort properties of mattresses. To our best knowledge, there has not been any study conducted validating the thermal comfort results of a benchtop tester using

human comfort trials on mattresses. The aim of this study is to validate the objective measurements from a thermal seat tester experiment and prove that test subjects perceive thermal sensations and show physiological changes similar to the test device's measurements. The human comfort trials on the mattresses had a duration of 60 minutes which was selected compare both short term differences (initial 30 minutes) and long term differences as analyzed in the previous two experiments using the benchtop tester and thermal manikin.

## **5.2 Experimental Method and Materials**

### ***5.2.1 Materials***

The experiments were conducted in an environmental chamber on a bedding system. The location of the bedding system remained consistent throughout the series of experiments to control for local air flows. The experiments in the environmental chamber were carried out at 22°C and 65% relative humidity (RH).

The bedding system consisted of an adjustable mattress frame, a box spring, a mattress, a pillow with a nonwoven cotton pillow case, a nonwoven cotton fitted sheet, thin nonwoven cotton sheet, and a polyester duvet cover. The bedding system setup remained consistent throughout the series of experiments other than changing out the mattresses. Keeping the same bedding for each experiment was necessary to prevent any stored modifiers or bias from past experiences held by the test subject from influencing their results [20]. The mattresses used for this study were all twin size mattresses. The specifications for

the three mattresses (A, B, and C) are shown in Table 10 below. Mattress A was a polyurethane (PU) foam mattress, Mattress B was an innerspring mattress, and Mattress C was a PU foam mattress enhanced with phase change materials (PCMs).

*Table 10 – Mattress Specifications for Human Trials*

Experimental Name:	Mattress A	Mattress B	Mattress C
Mattress Construction:	PU Foam	Innerspring	PU Foam with PCMs
Dimensions (cm): (LxW)	185 x 94	202 x 97	193 x 91
Thickness (cm):	25	20	31
Weight (kg):	18.15	14.95	27.20
Density (g/cm <sup>3</sup> ):	0.0417	0.0381	0.0499

There were twelve test subjects (six male, six female) used in the experiment. Subjects were required to weigh less than 136 kg, be no taller than 193 cm, and be a non-smoker to be qualified for the experiment to reduce variation between subjects. All test subjects were between the ages of 19-23. The average age of the test subjects was 21.25 (1.21), average weight was 72.97 (13.36) kg, and average height was 173.92 (9.62) cm. Prior to each test subject's first experiment, volunteers were asked to fill out a health screening questionnaire to evaluate the subject's ability to complete the experiment without

compromising their safety or safety of other test subjects. At this time, test subjects were also provided with an informed consent form, and familiarized with test devices and subjective evaluation forms to be completed throughout the experiments. After health screening questionnaire was reviewed by the primary investigator, the test subjects were allowed to participate in the experiment. This protocol was approved by the internal ethical review board (IRB) at NC State University.

Thermistors (MSR, 145W, Accuracy:  $\pm 0.1^{\circ}\text{C}$ ) were used to obtain the localized skin temperatures of the test subjects at the back of their left thigh, lower left back, upper left back, and on top of the left hand. Two K-type thermocouples (Measurement Computing, USB-603, Accuracy:  $\pm 2.5^{\circ}\text{C}$ , Resolution:  $0.1^{\circ}\text{C}$ ) connected to a data logger were placed on top of each mattress in the middle under the fitted sheet. The first thermocouple was placed 3 inches below the bottom of the pillow to capture the upper back contact area and the second thermocouple was placed 18 inches below the first thermocouple to capture the lower back contact area of the test subjects. The data logger was attached to the side of the mattress to not affect the study.

### ***5.2.2 Experimental Procedure***

Before each experiment, the test subjects were provided with a 100% cotton T-shirt, polyester shorts, and cotton socks to wear for the experiment. Here, subjects were also fitted with thermistors for local skin temperature measurements at the back of their left thigh, lower left back, upper left back, and on top of the left hand.

Once the test subjects were dressed in the testing garment and fitted with the test devices, subjects were lead to a room where they were allowed to acclimatize to the environment for 30 minutes during which subject were to sit on stools and relax (read magazines, talk to research team member, etc.). The weight of the test subject was recorded 15 minutes into the acclimatization period, whereafter no drinking was allowed until the end of the protocol. After this initial weight recording, subjects were provided and completed their first subjective thermal comfort evaluation form. After the 30 minutes of acclimatization had expired test subjects were lead into the environmental chamber and asked to lay on the mattress in the supine position for 60 minutes without moving. Test subjects were to bring the cotton sheet and duvet cover to their neck and place their hands by their sides. Immediately upon laying on the mattress, after 5 minutes, 10 minutes, and every 10 minutes to follow the test subject was asked to complete the thermal comfort subjective questionnaire. The test subject was read aloud each question and answers so that the subject did not have to move during the experiment.

### ***5.2.3 Data Analysis***

After completing the experiments, the data files were transferred to begin data analysis. Run charts of the important measured variables (local and mean skin temperature, mattress interface temperature, and the subjective questionnaire results) were created to obtain a visual understanding of the data trends in the experiments.

While the graphs provided sufficient understanding of the data in the hour long timeframe of the experiment, they could not provide complete steady state values because of the length of time required to reach this state. For this reason, the curve fitting tool in MatLab R2014b by MathWorks® was used to obtain an estimate of the steady state skin temperature values and the time required to reach the estimated steady state. The equation used to calculate the curve fit is shown by Equation 22.

$$Eq\ 22: y = f(x); \text{ where } x = a * (1 - ce^{\frac{-x}{\tau}})$$

Where a = Steady State Skin Temperature ( $^{\circ}\text{C} \cdot \text{m}^2/\text{W}$ );  $\tau$  = Time Constant Indicating Time to Reach Steady State Skin Temperature (Minutes); and c = a Scaling Constant to Fit the Data Optimally.

The statistical significance of the notable data trends obtained from both the graphs in and the curve fitting tool were calculated by using one-way ANOVA tests for the curve fit skin temperatures and repeated measures ANOVA tests for the mattress interface temperatures and subjective questionnaire results in JMP Pro 11 by SAS®.

### 5.3 Results

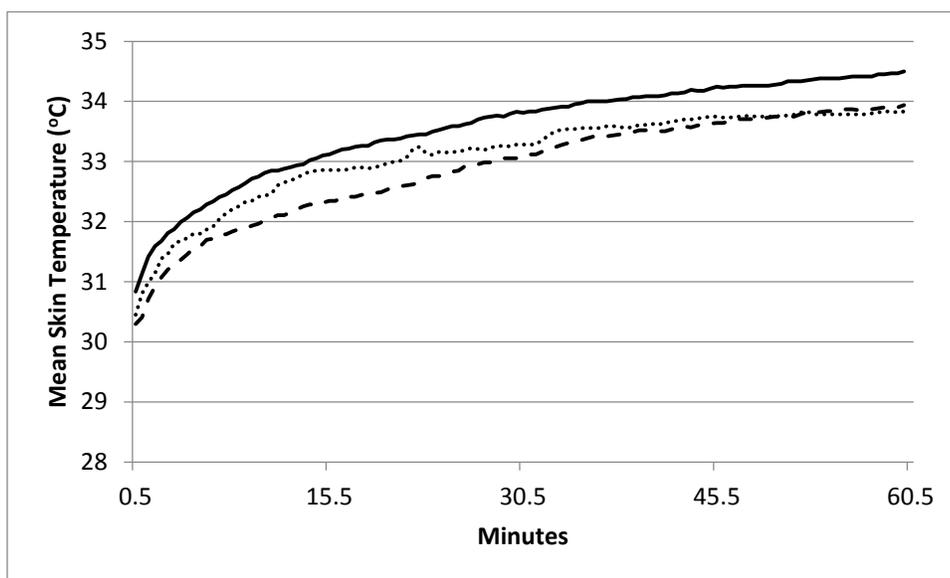
Figure 38 shows the mean skin temperature for a single test subject on each of the three mattresses. The mean skin temperature of the test subject increases for the entirety of the experiment. For this reason, the Curve fitting of mean skin temperatures of test subjects

in MATLAB produced steady state mean skin temperatures and tau time constants. The mean skin temperature was produced by averaging the four local skin temperatures. The mean steady state skin temperatures did not produce any significant differences between the three mattresses ( $p = 0.2253$ ) as shown in Figure 39a. The time constants ( $\tau$ ) in Figure 39b, however, did show significant differences between the mattresses ( $p = 0.0018$ ). Mattress C has significantly higher time constants than Mattress B and has notably higher values than Mattress A.

Mattress interface temperatures showed more prominent differences in the first 30 minutes of experimentation. For this reason, the final 30 minutes of the mattress trials were omitted for analyzing the mattress interface temperatures, and there was no added benefit of curve fitting the data. Repeated measures ANOVA testing of the average mattress interface temperature at both the upper and lower regions showed significant differences between the mattresses. Mattress C has a lower mean interface temperature than Mattresses A and B in the first 15 minutes and this difference decreases as the experiment continues as shown in Figure 40 and Figure 41. In the repeated measures ANOVA,  $p = 0.0032$  for the upper region and  $p = 0.0218$  for the lower region of the mattress indicating there are differences found when considering both time of the experiment and mattress.

Thermal comfort subjective questionnaires showed statistical differences after performing a repeated measures ANOVA. Four of the seven questions regarding thermal comfort resulted in significant differences being found using the p-value. Figures 42, 43, 44 and 45 show the average value given by the test subject at each questionnaire time during the

experiment. In Figure 42, the scores given from Mattress C from T1-T10 were significantly lower ( $p = 0.0181$ ) than those of Mattresses A and B which were not significantly different. Perception of thermal comfort at the back showed that subjects also felt that Mattress C produced a significantly cooler sensation ( $p = 0.0127$ ) than Mattresses A and B as shown from T1-T20 in Figure 43. Subject thermal comfort perception at the waist showed significant differences ( $p = 0.0073$ ) where subjects recorded much lower scores for Mattress A and C at T1 than for Mattress B as shown in Figure 44. The differences between the mattresses was also significant for thermal comfort perception at the legs ( $p = 0.0407$ ) as shown in Figure 45.



*Figure 38 – Mean Skin Temperature of a Test Subject. The mean skin temperature increases throughout the experiment on each mattress. Mattress A (solid line) has a higher mean skin temperature than Mattress B (dotted line) and Mattress C (dashed line).*

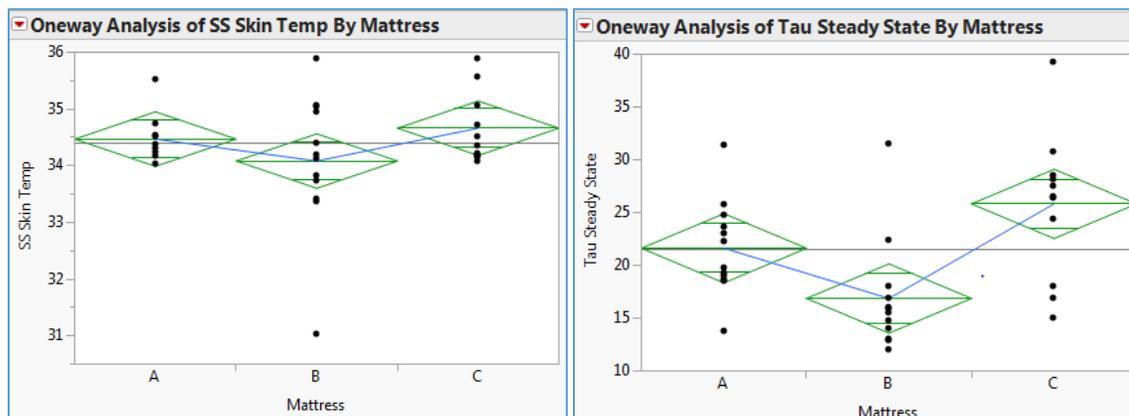


Figure 39a (left) – One-Way ANOVA Test of Steady State Skin Temperature. None of the three mattresses show significant difference.

Figure 39b (right) – One-Way ANOVA Test of  $\tau$  for Skin Temperature. There is a significant difference between the three mattresses. Mattress C has the highest value while Mattress B has the lowest value.

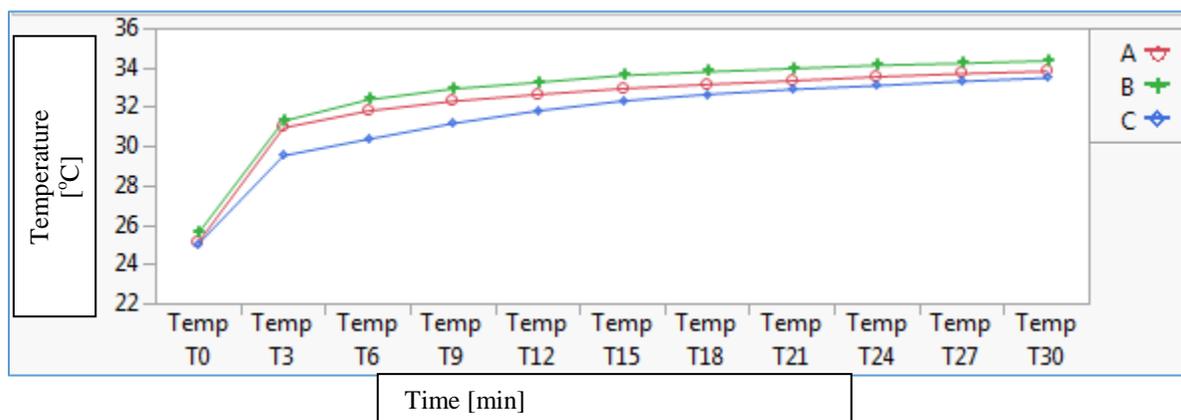


Figure 40 - Average Upper Back Mattress Interface Temperature during the First 30 Minutes of the Experiment. Mattress C has a significantly lower upper back interface temperature than Mattresses A and B. Y axis is  $^{\circ}\text{C}$  and X axis is minutes.

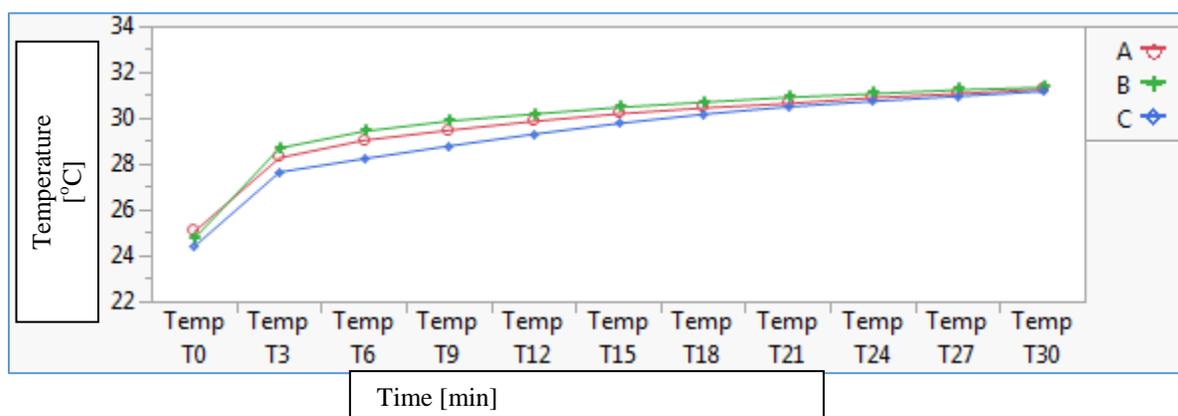


Figure 41 – Average Lower Back Mattress Interface Temperature during the First 30 Minutes of the Experiment. Mattress C has a significantly lower lower back interface temperature than Mattresses A and B. Y axis is °C and X axis is minutes.

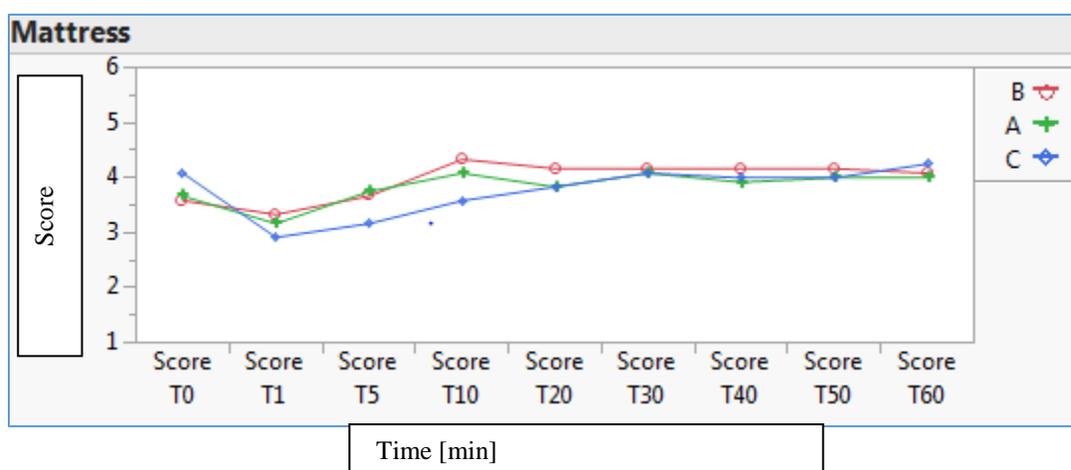


Figure 42 – Thermal Comfort Subjective Questionnaire: “How do you feel at this precise moment?” 1: Very Cold, 7: Very Hot. Mattress C appears to have a lower average score than Mattresses A and B from minutes 1-10. Y axis is °C and X axis is minutes.

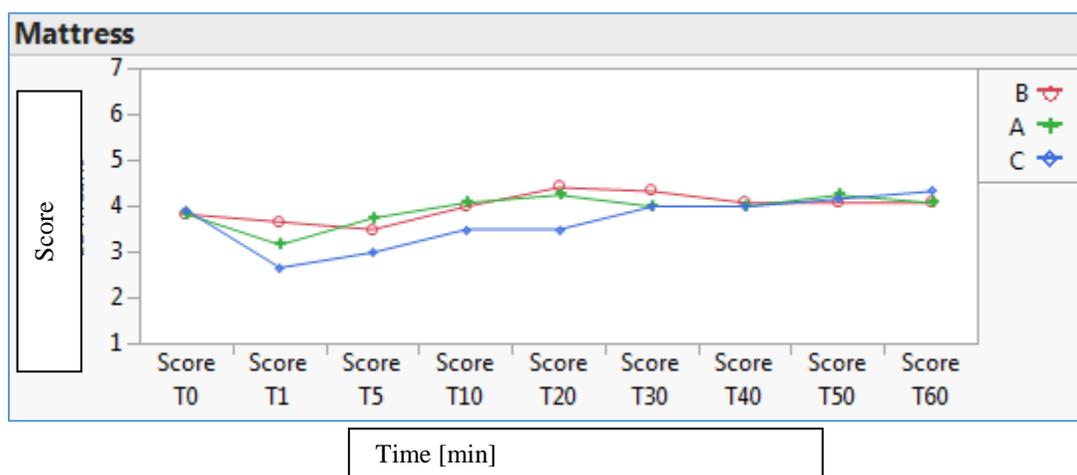


Figure 43 – Thermal Comfort Subjective Questionnaire: “At your back do you feel...” 1: Very Cold, 7: Very Hot. Mattress C appears to have a lower average score than Mattresses A and B from minutes 1-10. Y axis is °C and X axis is minutes.

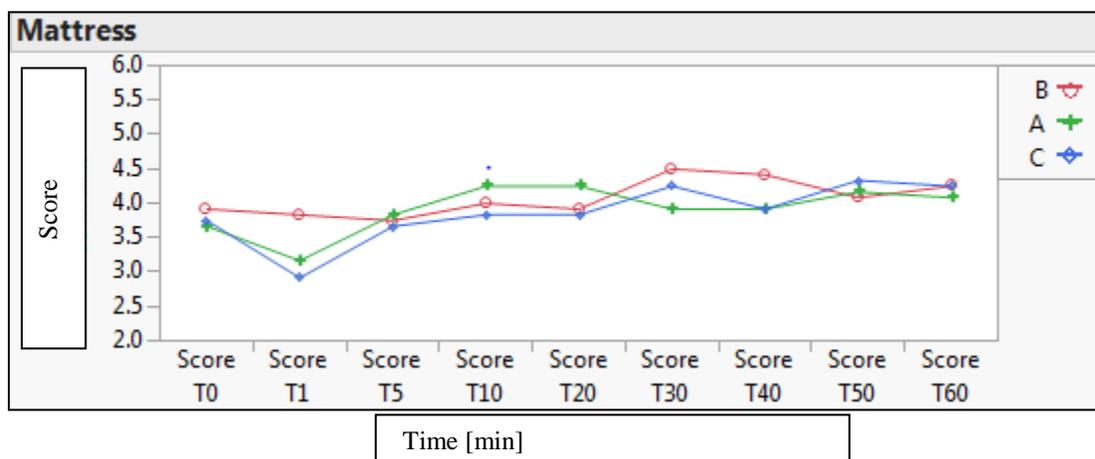


Figure 44 – Thermal Comfort Subjective Questionnaire: “At your waist do you feel...” 1: Very Cold, 7: Very Hot. The mattresses show less difference in thermal perception at the waist while Mattress C and B show a notable difference from Mattress A at T1. Y axis is perceived score and X axis is minutes.

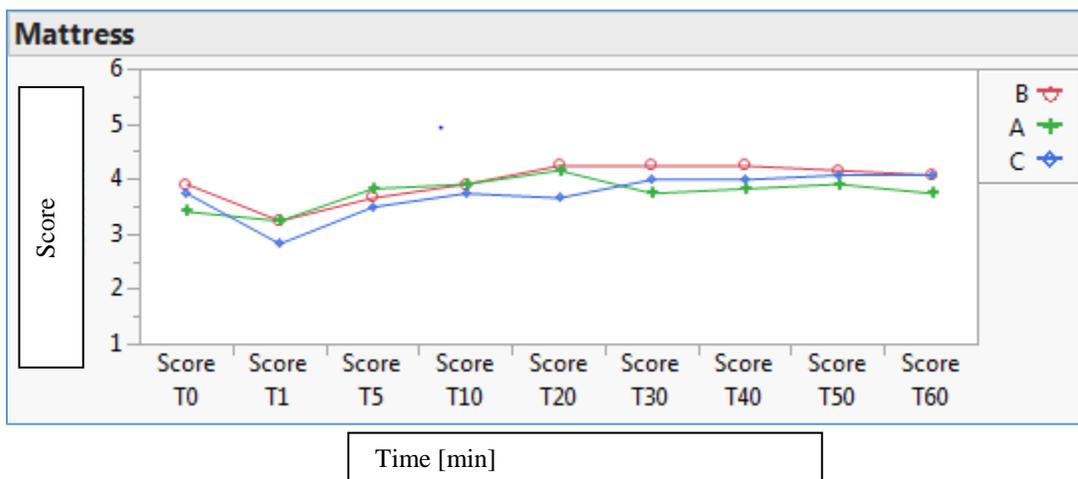


Figure 45 – Thermal Comfort Subjective Questionnaire: “At your legs do you feel...” 1: Very Cold, 7: Very Hot. The mattresses show less difference in thermal perception at the legs with Mattress C having lower values than Mattresses A and B from T1-T20. Y axis is perceived score and X axis is minutes.

#### 5.4 Discussion

Figure 39a showed that the steady state mean skin temperatures of the test subjects on each mattress were not significantly different from one another as deemed by a one-way ANOVA test even as Mattress B appeared to have a slightly lower average value than Mattresses A and C. This could be because the one hour duration of the experiment was not long enough for the body to be significantly affected and changed by the mattresses. The rate to reach steady state mean skin temperature (Tau time constant values) did show statistically significant differences between the mattresses as shown in Figure 39b. The higher Tau values

of Mattress C than Mattress B can be attributed to the PCMs in Mattress C which would delay an increase in skin temperature as the skin temperature caused the phase change to occur.

The repeated measures ANOVA test on the mattress interface temperatures of both the upper and lower back regions of the mattress showed statistical significance over time as shown in Figures 40 and 41 respectively. These differences were again attributed to the PCMs found in Mattress C. While the repeated measures ANOVA test did not explicitly describe what time points the Mattresses are statistically different from one another, the differences appear to be occurring before the 15 minute mark of the experiment. This is the point where the PCMs found in Mattress C at the upper and lower back locations have completely changed their physical state from solid to liquid and the delay of increase in temperature due to the phase change has expired. After this 15 minute point, the mattress interface temperatures at the upper and lower back regions show no significant difference.

Mattress C was perceived as being significantly cooler than Mattresses A and B during the first 10 minutes of the experiment from the subjective evaluations as demonstrated by the overall thermal perception shown in Figure 42. Subjects could also differentiate between Mattress C vs. Mattresses A and B when asked about their localized thermal perception at their back (Question 3 from the Questionnaire) as shown in Figure 43 where there were significant differences in the curves during the first 20 minutes of the experiment. The lower scores of Mattress C during these time frame can be attributed to the PCMs going through phase change from solid to liquid where there is a delay of increase in mattress

interface temperatures in the upper and lower back regions. The PCMs are expected to be the main contributing factor to these differences because Mattresses A and C are both foam mattresses yet have different results while Mattress B (an innerspring mattress) was perceived thermally similar to the test subjects.

These human comfort results are in line with and show similarities to the results of the experiment using a thermal seat tester and the thermal manikin data. The surface temperature of the test device showed a delayed increase on Mattress C while having nearly surface temperatures for Mattresses A and B. The surface temperature of the test device was also significantly lower on Mattress C than for Mattresses A and B. This lower surface temperature is indicative of the cooler thermal perception experienced by the human subjects. The rate at which the ST2-XL test device reached a steady state ( $\tau$  value) was also significantly lower for Mattress B, as it was in the human comfort trials. Mattress C had the highest average  $\tau$  value in the human comfort trials and the seat tester experiments, but Mattress A had the highest average  $\tau$  value in the manikin experiment. The average  $\tau$  values for each mattress were lower in the human comfort trials than for the experiments with the test devices. This faster rate to steady state is expected to be a result of the human body being able to respond to environmental changes faster than the test devices.

This test method was capable of detecting thermal comfort differences between the mattresses through subjective scoring techniques like the experiments from Bartels and Jonas et. al [26]. However, the present study was also able to find localized thermal comfort differences at the back between materials instead of solely overall thermal comfort.

Furthermore, the seat tester experiments and the subjective responses of the subjects described similar thermal properties of the mattresses related to comfort like the experiments performed by Bartels did for aeroplane seats.

## **5.5 Conclusion**

It was demonstrated that the human comfort trials detected significant differences between the thermal properties of these three mattresses. The rate to reach steady state skin temperature with curve fitting showed that differences between the mattresses could be found in the long term, while measurements of the mattress interface temperature and subjective thermal comfort scoring showed that the thermal properties between the mattresses also differed over a shorter time period. The results from this study produce similar results to tests conducted on the same three mattresses using a thermal seat tester and validates that the test device provides accurate and meaningful data in relation to how thermal comfort would be perceived by a human lying on the mattress.

## **CHAPTER 6: Repeatability of Thermal Seat Tester and Test Method**

### **6.1 Purpose**

Previously in Chapter 3, the thermal seat tester and a corresponding test method was developed to produce repeatable data that found significant differences between the three mattresses in both the short term and long term at three different temperatures. However, this set of experiments performed only 3 repetitions on each mattress for a total of 9 tests. This

number of experiments, while sufficient for proving differences between the mattresses, might not be large enough to fully validate the repeatability of the test method and test device. For this reason, at least 5 additional tests using the same mattresses as before (ref. Table 6 on page 59) and according to the same test procedure as described in Chapter 3 were performed at 20°C and 65% relative humidity. The conditions of the chamber, mattresses, bedding materials, operator, and test method were all kept constant between the two sets of experiments. The original data set from Chapter 3 and the repeated experiments were performed 18 months apart.

## 6.2 Results

The initial surface temperature of Mattress C in the first minute of the experiment is significantly lower ( $p = 0.0014$ ) than Mattress A or Mattress B as seen in Figure 46. This initial surface temperature of the test plate is lower than the 35°C temperature setpoint on all three mattresses. Analysis of the peak surface temperature of the test plate also produced statistically significant differences between the mattresses. Figure 47 shows that Mattress C produces a lower peak surface temperature than both Mattress A and Mattress B ( $p = 0.0363$ ).

The first 30 minutes of the experiment has shown differences between the mattresses. This is most noticeably seen by analyzing the surface temperature of the test device. Some of the characteristics that were of particular interest were the initial lowest temperature, peak temperature, and time-to-peak temperature differences between the mattresses. These

average values for each mattress are shown in Table 11. The time-to-peak surface temperature is higher for Mattress C than Mattress A and Mattress B.

The shape and steady state values of the thermal resistance curves were characterized by a curve fit. The same irregularity of the initial 30 minutes of the experiments caused by the device stabilizing as seen in the Figure 25 and 26 called for the initial 30 minutes to be omitted during curve fitting to produce an accurate curve fit and meaningful Tau and steady state Reff values for further analysis. The one-way ANOVA of steady state Reff in Figure 48 showed that the ST2-XL and test method shows significant differences ( $p < 0.0001$ ) between Mattress B to Mattresses A and C. Mattress B had a lower steady state Reff value than Mattress A and Mattress C. The one-way ANOVA of  $\tau$  (Time Constant) in Figure 49 showed that the ST2-XL and test method shows significant differences ( $p < 0.0001$ ) between Mattress C to Mattresses A and B. Mattress C had a higher Tau value than Mattress A and Mattress B.

*Table 11 – Average Initial Temperature, Peak Surface Temperature, and Time-to-Peak Surface Temperature for Each Mattress at 20°C during Repeatability Testing. Mattress C has a significantly lower initial surface temperature, peak surface temperature, and higher time-to-peak surface temperature than Mattresses B and C.*

Mattress:	Initial Surface Temperature (°C)	Peak Surface Temperature (°C)	Time to Peak Surface Temperature (minutes)
A	34.73	35.90	5.80
B	34.75	35.89	5.67
C	34.61	35.46	9.57

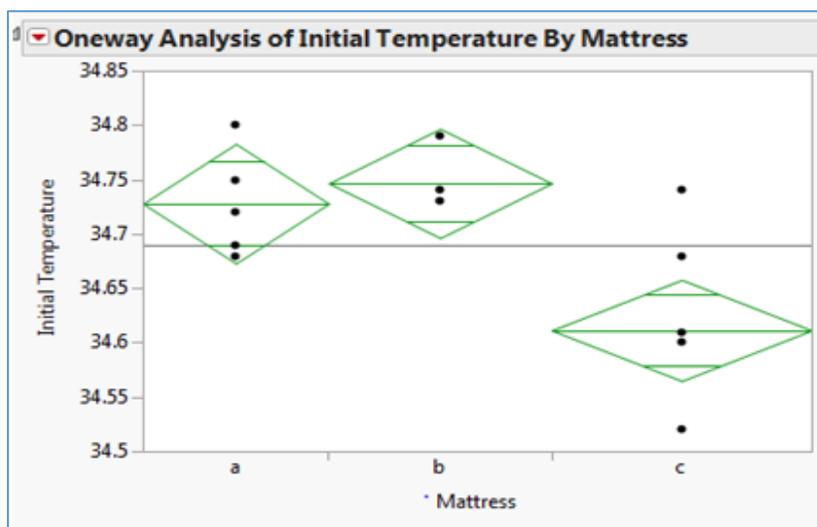


Figure 46 – One-Way ANOVA Test of Initial Surface Temperature ( $^{\circ}$ C) of the ST2-XL during Repeatability Testing. Mattress C has a lower initial surface temperature than Mattress A and Mattress B.

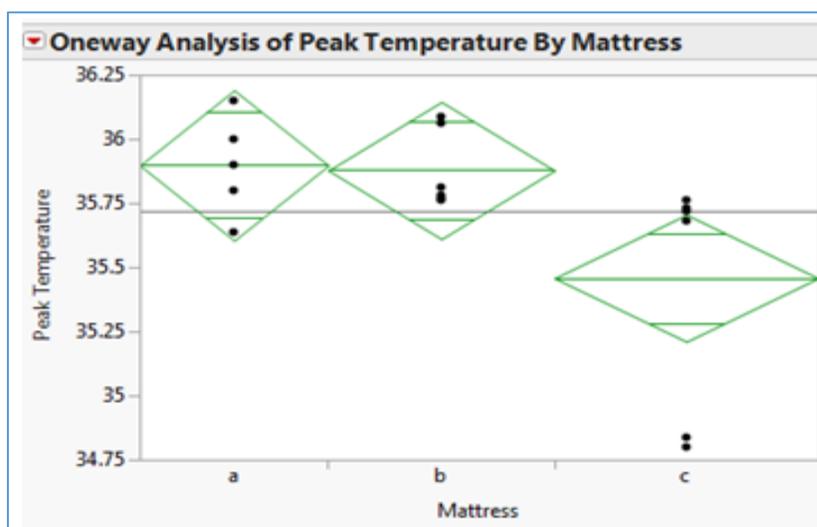


Figure 47 – One-Way ANOVA Test of Peak Surface Temperature ( $^{\circ}$ C) of the ST2-XL during Repeatability Testing. Mattress C has a slightly lower peak surface temperature than Mattress A and Mattress B.

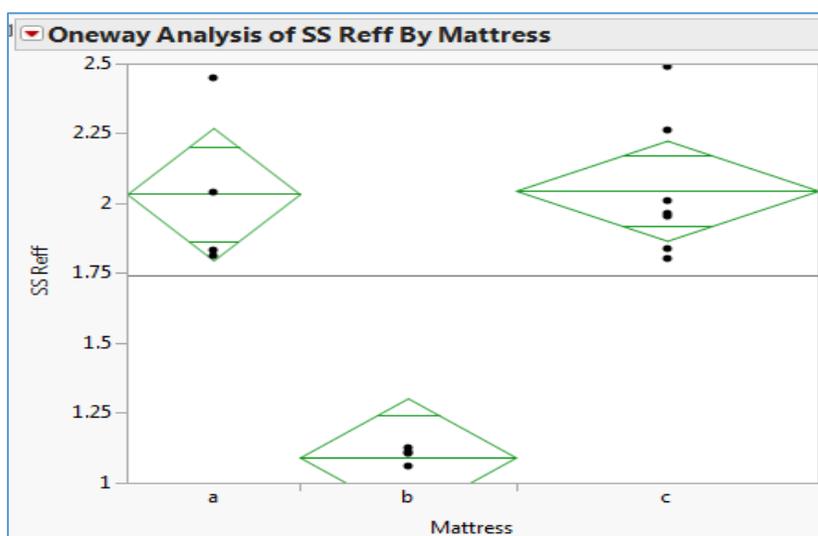


Figure 48 – One-Way ANOVA test of Steady State Reff from Curve Fitting for Each Mattress during Repeatability Testing. Mattress B has a significantly lower steady state Reff than Mattress A and Mattress C.

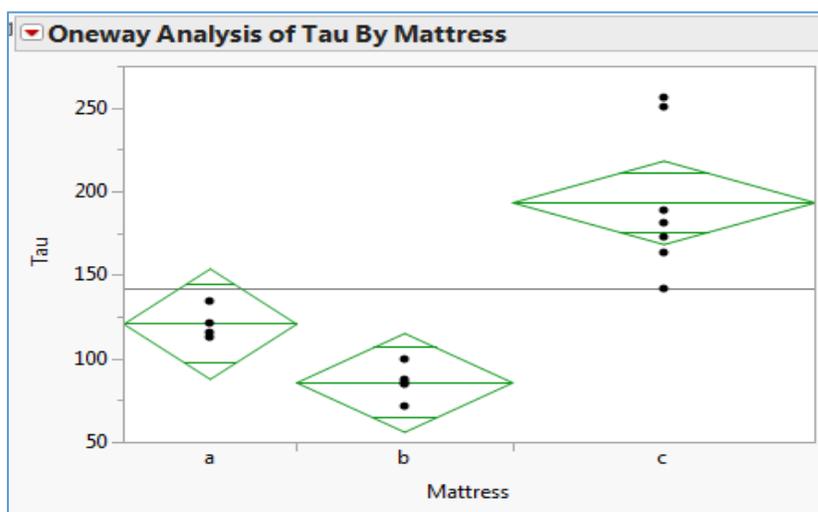


Figure 49 – One-Way ANOVA Test of Tau Time Constant from Curve Fitting for Each Mattress during Repeatability Testing. Mattress C has a higher value than Mattress A and Mattress B.

### 6.3 Discussion

As seen in Table 11, the general shape of the graph of surface temperature within the first 30 minutes is the same as it was in previous tests. Each mattress had an initial decrease from the 35°C setpoint of the test plate due to contact with the mattress and experienced a cooling sensation through conduction. Also, each mattress experienced an increase in surface temperature from this point and surpassed the 35°C temperature setpoint before slowly decreasing to the setpoint within the first 30 minutes as seen in the original data set. Table 11 also shows us that the initial surface temperature and peak surface temperature of Mattress C is the lowest and that the time-to-peak surface temperature is the highest on Mattress C compared to Mattress A and Mattress B. These characteristics of Mattress C are consistent with the results from Chapter 3 and are likely caused by the presence of PCMs towards the surface of the mattress which delays the increase in temperature of the test plate. In Figure 46, the one-way ANOVA test of initial surface temperature between the mattresses shows that the difference is significant. In Figure 47, the one-way ANOVA test of peak surface temperature between the mattresses shows that the difference is significant. This difference in initial surface temperature and peak surface temperature was significant for the original tests as shown by the error bars on Figure 24 (page 64) in Chapter 3.

Differences were found between the two data sets in the first 30 minutes of surface temperature as well. A significant difference was found between the initial surface temperature of Mattress A and Mattress B whereas this difference was not found in the

repeated experiments. Numerical differences were even more noticeable between the two data sets. The average initial surface temperature was higher in the original data set than the repeated tests by 0.06 °C, 0.13 °C, and 0.08 °C for Mattresses A, B, and C respectively. The average peak surface temperature was also higher in the original data set than the repeated tests by 0.27 °C, 0.26 °C, and 0.51 °C for Mattresses A, B, and C respectively. The average difference between the initial surface temperatures of the data sets was 0.09°C higher in the original tests than the repeated tests. The average difference between the peak surface temperatures of the data sets was 0.35°C higher for the original tests than the repeated tests. The average difference between the time-to-peak surface temperatures of the data sets was 1.03 minutes lower for the original tests than the repeated tests. This was most likely a result of the test device not being calibrated between the times of the experiments (18 months).

Analysis of the Tau time constant and steady state Reff long-term variables showed similarities between the original and repeated data sets. These long term variables are most affected by the construction and density of the mattresses. Figure 48 showed that the steady state Reff value of Mattress B was significantly lower than in Mattress A and Mattress C. This difference between the mattresses was also found in the original tests with Mattress B having a lower steady state Reff value than Mattress A and Mattress C (ref. 27 on page 66). Mattresses A and C were not significantly different from each other in either data set in regards to steady state Reff using the ST2-XL. The numerical difference between the two data sets was not very large in regards to steady state Reff. The largest difference between them was that the average steady state Reff of Mattress B was 0.08 W/m<sup>2</sup>C higher in the

original data set than in the repeated data set. The original data set had a higher average steady state  $R_{eff}$  than the repeated tests for Mattress A ( $0.05 \text{ W/m}^2\text{C}$ ) and Mattress C ( $0.02 \text{ W/m}^2\text{C}$ ) as well. The average difference between the steady state  $R_{eff}$  of the data sets was  $0.05 \text{ W/m}^2\text{C}$  higher in the original tests than the repeated tests. Figure 49 showed that the Tau time constant of Mattress C was significantly higher than Mattress A and Mattress B. This was the case in the original data set as well except that in the original data set Mattress B was significantly lower than Mattress A. The Tau values showed less consistent values from the original data set to the repeated data set. The Tau value of the original data set was higher on Mattresses A (17.9 minutes) and B (4.8 minutes), but lower on Mattress C (-13.8 minutes) in comparison to the repeated tests. These differences were again most likely caused by the absence of calibration between the times of the two sets of experiments. This would be the most likely cause because the conditions of the chamber, mattresses, bedding materials, operator, and test method were all kept constant between the two sets of experiments.

#### **6.4 Conclusion**

These experiments have shown that the thermal seat tester and the described test method are capable of characterizing the thermal properties of these three mattresses in a repeatable manner. Significant differences were still found between the mattresses in both the short term measurements of initial surface temperature, peak surface temperature, and time-to-peak surface temperature and in the long term measurements of tau time constant and

steady state  $R_{eff}$  from curve fitting. The absence of calibration lead to slightly different values between the two data sets. However, these differences did not alter the significance of the data trends found between the mattresses. In future work, the device should be recalibrated before beginning the experiments. This would provide a better indication of the level of repeatability of the test device and test method for characterizing mattress thermal properties.

#### **CHAPTER 7: Conclusions and Recommendations:**

Results from this research demonstrated the ability of the ST2-XL and thermal manikin to predict the thermal properties of mattresses related to comfort. This was accomplished by performing a thorough literature review which provided the necessary information to develop repeatable test methods. Using the ST2-XL and thermal manikin in dry conditions at 35°C enabled this research to predict mattress thermal comfort in the short term by analyzing the changes in surface temperature of the devices and in the long term by performing curve fits of the thermal resistance measurements. Short term and long term measurements were necessary for thermal comfort because they can be used to describe how thermally comfortable a person will feel as they are getting into the mattress as they go to bed and how they will feel over the course of a night.

Through this work, it was established that the ST2-XL and described test method were fully capable of describing the thermal comfort properties of the mattresses which could be explained by the construction of the mattress and provide repeatable data. The ST2-XL

and test method were also shown to predict the same trends in thermal comfort properties of the mattresses in three different ambient temperature conditions that were likely to be found in a standard home.

The thermal manikin and described test method was also capable of describing the thermal comfort properties of the three mattresses in the short and long term in a repeatable manner. However, the thermal manikin provided less significant differences in many of the thermal properties than the ST2-XL. The ST2-XL is perhaps more capable of describing the thermal comfort properties of the mattresses because its test region is in full contact with the mattress and does not vary in pressure points like the contour of the manikin does.

The test method results of the ST2-XL and thermal manikin were validated by performing human comfort trials. Here, the analysis of the mean skin temperature, mattress interface temperature, and subjective thermal comfort questionnaires revealed that test subjects found similar thermal sensations as predicted by the test devices through both subjective and objective data collection. This was an important finding because the test methods show that they provide meaningful data that is similar to the thermal sensation experienced by a human.

### **7.1 Implications for Future Research**

This research has brought about a variety of information that will be beneficial for the mattress industry and all users of mattresses. However, there are still questions left unanswered at the end of this research that could provide meaningful information into

bettering these test methods. An investigation into classification of mattresses into different levels of provided thermal insulation in both the short term and long term would be beneficial for the industry and consumers. This classification would allow consumers to purchase mattresses based on their own personal insulation needs. Classification was not accomplished during the present research due to a lack of mattresses being tested during the development of the test methods. Additional experiments using recalibrated ST2-XL and thermal manikin systems would aid in the understanding of the true repeatability level of these test methods. Finally, supplementary testing would allow researchers to obtain the optimal method for interpreting data supplied by the ST2-XL and thermal manikin.

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