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Predicting the Effect of Temperature on the Shock Absorption Properties of Polyethylene Foam

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PREDICTING THE EFFECT OF TEMPERATURE ON THE SHOCK ABSORPTION PROPERTIES OF POLYETHYLENE FOAM

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Packaging Science

by
Samuel Dylan McGee
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Accepted by:
Dr. Gregory S. Batt, Committee Chair
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Abstract

Polyethylene (PE) foam is a material used commonly in protective packaging for its shock absorption properties. When developing a package design intended to mitigate shock to the product, decisions are typically made based on established cushion evaluation procedures performed at standard laboratory conditions. Distribution environment temperatures, however, can vary greatly from the condition at which these materials are assessed. The research presented in this paper utilizes the stress-energy method of cushion evaluation, and highlights temperature-dependent trends in the stress-energy equations of PE foam tested at twelve different temperatures, ranging from -20°C to 50°C . A quadratic polynomial is used to describe the variation in the stress-energy equation coefficients over the temperature range evaluated. The model developed enables cushion curve prediction for any static stress, drop height, material thickness, and temperature expected over the intended range of use of the material. This model is validated by performing additional impact testing of samples at various temperatures and comparing experimentally obtained acceleration values to those predicted by the model. Further model analysis is performed to estimate the optimal static stress for the material at any temperature within the range tested, and to study the variation with temperature of this optimal point. Results reveal that the model developed is capable of predicting the shock absorption properties of the material within the range of parameters tested, and that the optimal static stress of the material decreases by about 60% as temperature increases from -20°C to 50°C .

Dedication

To God the Creator and Sovereign Lord of all—My first fruits. To Him be the glory.

Now to Him who is able to do immeasurably more than all we ask or imagine, according to His power that is at work within us, to Him be glory in the church and in Christ Jesus throughout all generations, for ever and ever! Amen.

(Ephesians 3:20,21)

And to my wife, Allison Grace, the love of my life and my best friend.

Acknowledgments

First and foremost, I must acknowledge God the Father, the loving, just, all-knowing Creator and Redeemer. The enduring work of the Father, Son, and Holy Spirit alone provide the grace, redemption, life, mind, skills, experiences, and relationships necessary to be a sub-creator in a beautiful yet broken world. Thank you for ineffable grace, love unearned and undeserved, and Your relentless work of redemption in my stubborn heart. May this effort bring glory to You alone, as we eagerly await the fulfillment of eternity with You.

For our light and momentary troubles are achieving for us an eternal glory that far outweighs them all. So we fix our eyes not on what is seen, but what is unseen. For what is seen is temporary, but what is unseen is eternal.

(2 Corinthians 4:17,18)

I thank also my wife and best friend, Allison Grace. Her love, patience, perseverance, forgiveness, planning, and encouragement have kept me on track throughout this process, and throughout our life together. Allison, thank you for your willingness to let God use you to work incredible things in our lives. You make me better. I love you—Cross my heart.

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I must thank also my Clemson community: my family at Clemson Presbyterian Church, who have been my anchor; brothers who have spoken truth and encouragement into my life; fellow hobbyists who have reminded me of the beauty that surrounds; and my Clemson University family—students and teachers—who have given me countless opportunities to teach, learn, and grow.

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Chapter 1

Introduction

When developing a package design intended to mitigate shock to a product, a packaging scientist will consult cushion curves to define the appropriate cushioning material parameters. A cushion curve is a two-dimensional tool characterizing the shock absorbing properties of a cushion material over a range of static stresses. These curves depict the ability of a material in a given application to mitigate shock to a product. This information aids in the development of protective packaging systems. Cushion curves are developed only at standard laboratory conditions of 23°C. Cushion materials, however, are often polymer foams, the mechanical properties of which are known to be temperature dependent. Many polymer foams undergo significant property changes with variations in temperature: As temperature increases, molecular motion increases and the polymer becomes more pliable and less resistant to deformation. Conversely, as the temperature is lowered, the material becomes stiffer and less malleable. These changes affect the shock absorption properties of the foam. Since real world use of these materials is over a wide range of temperatures, often extending from -20°C to 50°C, understanding the effect of temperature on the mechanical performance of polymer foam cushioning material is important to optimum protective packaging design.

The research presented in this manuscript utilizes the stress-energy method of cushion evaluation, and observes temperature-dependent trends in the stress-energy equations

of polyethylene (PE) foam tested at twelve different temperatures, ranging from -20°C to 50°C . A polynomial model is used to describe and predict the variation of these equations, and thus changes in cushion properties, over the temperature range evaluated. The objective of this work is to better understand the performance of PE foam in its conditions of use, thereby reducing costly product damage by supporting the development of more effective protective packaging systems.

Chapter 2

Review of Literature

2.1 Physical Hazards in the Distribution Environment

Products in transit face numerous hazards in the distribution environment, including compressive forces, shock, vibration, and temperature and humidity extremes. Mechanical shock, one of the most damaging hazards in the distribution environment, is defined in the packaging field as a rapid change in velocity relating to the physical movement of products and packages. In the distribution environment, shock results from the sudden acceleration or deceleration caused most commonly by handling drops, but also inflicted by tosses, lateral kicks, or vertical impacts from other packages (Fiedler, 2009). The abruptness of a shock is characterized by the duration of the impact, typically expressed in milliseconds. The duration of a shock experienced by a packaged product dropped onto a hard floor is in the range of 2-50 milliseconds, and is largely dependent upon the type and quantity of cushioning material incorporated in the packaging system. Cushioning mitigates an impact by increasing the duration of a shock. Cushioning materials enable an impact to be stretched across a longer period of time, thus reducing the maximum shock experienced by the product.

The rate of velocity change of a body upon impact is described by the term acceleration, or deceleration, and is measured in G's. For a given foam, acceleration is inversely

related to shock duration; this indicates that the greater the shock duration of an impact, the lower the acceleration experienced by the product. As discussed, shock durations, and thus acceleration levels, are reliant upon the effect of cushioning material. A system lacking adequate cushioning could experience peak accelerations of 500–1000 G. With effective cushioning, however, accelerations experienced by the product can easily be reduced to 15–100 G. The selection of appropriate cushioning material depends on the weight and fragility of the product, as well as the anticipated height and frequency of drops the package will encounter (Fiedler, 2009).

Cushion materials work by reducing the rate of velocity change, and thus the peak acceleration—shock—experienced by a product. This is accomplished by a cushioning material deforming to enable a product to come to a stop over a longer period of time. Because of their resiliency and ease of deformation, polymer-based foams are some of the most common forms of cushioning material. These low-density cellular materials can effectively absorb the energy of an impact and increase the duration of shock, thus reducing costly product damages caused by large accelerations (Hanlon et al., 1998).

2.2 Conventional Evaluation of Cushioning Material

The most commonly used industry-recognized procedure for cushion evaluation is ASTM D1596 - Standard Test Method for Dynamic Shock Cushioning Characteristics of Packaging Material. This technique utilizes a falling guided platen assembly to directly impact a cushion specimen. The platen drop height is set to simulate the impact velocity a packaging system may experience in the distribution cycle. This is known as the effective free fall drop height. An accelerometer fixed to the platen records the shock pulse generated from the platen impacting the cushion specimen. The shock pulse is then filtered to determine peak acceleration and pulse duration. The variables of drop height, static stress, and number of impacts are modified to generate a full family of cushion curves (ASTM, 2014a). Cushion curves depict a plot of static stress—defined as platen weight over specimen area—versus

output acceleration. The static stress that yields the lowest output acceleration is considered the optimum static stress, as it is the point where the cushioning material most effectively mitigates shock to the product. It is important to note that a cushion curve for a given static stress range is specific to the material, specimen thickness, and platen drop height utilized in testing. Therefore, generation of a full set of cushion curves for the reasonable working range of a material would require over 10,000 drops and about 175 hours of lab time (Daum, 2006).

A second commonly used procedure for cushion evaluation is ASTM D4168 - Standard Test Method for Transmitted Shock Characteristics of Foam-in-Place Cushioning Materials. This method utilizes a user-created foam-in-place package with a dummy block. An accelerometer mounted to the interior of the block is used to measure shock response. A free fall drop tester or shock machine is utilized to attain the velocity change required to simulate a range of drop heights. From the acceleration values obtained, a family of cushion curves is generated (ASTM, 2014c).

Concerning environmental conditions for cushion testing, both ASTM D1596 and ASTM D4168 state that, if no other requirements exist, testing should be performed at standard conditions of 23°C and 50% relative humidity. If attempting to evaluate a material at special or non-standard conditions, ASTM designates that conditioning should be performed for a period of time sufficient to achieve and sustain equilibrium of the specimen with the conditioning environment. Furthermore, when testing at special conditions, the specimen should be returned to the conditioning chamber between drops or impacts, and should not be out of the special condition for longer than 30 minutes. Alternatively, both ASTM D1596 and D4168 mention that the test apparatus can be moved into the chamber, where testing can be carried out (ASTM, 2014a,c).

2.3 Evaluation of Cushioning Material Using Stress-Energy Relationship

A proposed enhancement to ASTM D1596, the stress-energy method of cushion evaluation demonstrates that the energy absorbed per unit volume of a cushion material is equal to the area under the dynamic stress-strain curve for that material. Initially developed by Dr. G. Burgess in 1990, this method presents that because the stress-strain relationship is intrinsic to a given material, the transmitted acceleration of an object dropped onto that material can be predicted for any reasonable drop height or material geometry. Burgess suggested that this method presents the advantages of more concise and continuous cushioning data, streamlined integration with computer aided design, and significant reduction of laboratory time required to generate a full set of cushion curves (Burgess, 1990).

A simplification of Burgess's work, Dr. M. Daum in 2006 presented a procedure which leverages the stress-energy method to collect data for cushion evaluation. This method describes the shock absorption properties of a material by analyzing the relationship of static stress, drop height, cushion thickness, and impact mass acceleration. The stress-energy method serves to condense all combinations of drop height, material thickness, and static stress into a single equation capable of generating cushion curves for any reasonable combination of parameters (Daum, 2006). In this method, cushion testing is performed at several discrete energy levels, and dynamic stress is plotted versus dynamic energy. An exponential trendline of the form presented in Eq. (2.1) is fit to this data set, Fig. 2.1.

The dynamic stress, y , and dynamic energy, x are defined in Eqs. (2.2), where G is the maximum acceleration of the impacting mass, s is the static stress or w/A (weight / area), h is the equivalent free fall drop height, and t is the specimen thickness. A and B represent the model coefficients identified in the curve fit operation.

$$y = Ae^{Bx} \tag{2.1}$$

Figure 2.1: Dynamic Stress versus Dynamic Energy for Ethafoam® 150 at 23°C.

$$y = Gs \quad \text{and} \quad x = \frac{sh}{t} \quad (2.2)$$

Substituting Eqs. (2.2) into Eq. (2.1) and solving for the impact mass acceleration yields Eq. (2.3).

$$G = \frac{Ae^{B\frac{sh}{t}}}{s}. \quad (2.3)$$

Equation (2.3) can then be used to generate cushion curves for any reasonable cushion thickness and equivalent free fall drop height over a range of static stresses. To produce a cushion curve, drop height and cushion thickness are defined by the researcher, and the A and B coefficients defined by the curve fit operation are inserted. Based on these inputs, Eq. (2.3) is used to determine corresponding impact mass acceleration values for a range of static stresses. This data is plotted to produce cushion curves, Fig. 2.2 (Daum, 2006).

Research presented by P. Marcondes in 2007 assessed the minimum number of drops and energy levels needed to construct cushion curves using the stress-energy method. In

Figure 2.2: Cushion curve generated from stress-energy equation. Drop height: 24 in; cushion thickness: 2 in.

determining the minimum sample size necessary to produce cushion curves, this work sought to identify potential cost savings in reducing the amount of time and samples, as compared to the traditional method of cushion evaluation. In this study, stress-energy equations were fit to data obtained at 8–10 energy levels, referred to as the reference data. Stress-energy equations generated from a diminishing number of energy levels were statistically compared to the reference data curves on the basis of the slope and intercept of these fit lines. It was revealed that lines could be fit without statistical difference by using as few as 15 samples—five replicate impacts at three energy levels (Marcondes, 2007).

Work in 2010 attempted to compare the accuracy of the shock values predicted by the stress-energy method to cushion curves generated using ASTM D1596 (Mitchell et al., 2010). While this study reported some discrepancies greater than $\pm 5\%$ for parameters outside of the intended working range of the material tested, research presented by K. Paulin of Clemson University indicates that for reasonable static stresses and cushion thicknesses,

the stress-energy method yields results statistically similar to those of ASTM D1596, while reducing sample size and lab time. Paulin analyzed the accuracy of acceleration values predicted using the stress-energy method in statistical comparison to ASTM D1596. Cushion impact data was collected, and the goodness of fit of the stress-energy equation to that data was analyzed. Upper and lower confidence levels for the stress-energy equation were determined, and these were used to construct upper and lower confidence bounds for the generated cushion curves. In the final phase, cushion curves were produced for a range of thicknesses and drop heights using the traditional ASTM D1596 method, and compared to those generated by way of the stress-energy method. Results of this study indicate that although R^2 values for every respective stress-energy equation were greater than 0.96, R^2 value alone may not be sufficient to describe the goodness of fit of the stress-energy equation, and analysis of the root mean square error (RMSE) is a recommended addition. The results of this research indicate that five replicate impacts performed at four energy levels are sufficient to define the stress-energy equation of a material for reasonable drop heights, thicknesses, and static stresses (Paulin, 2012).

2.4 Assessment of Distribution Environment Temperature

In the contiguous United States, national average seasonal temperatures range from approximately 0°C in January to 23°C in July, representing a minimal temperature difference of 23°C in a given year. Data recorded by the National Oceanic and Atmospheric Administration (NOAA) reports that from 1901 to 2015, January temperatures in regions of the Northeastern U.S. averaged -16°C. Between 1901 and 2015, July temperatures in the Desert Basins region of the Southwestern U.S. averaged 37°C (National Oceanic and Atmospheric Administration, 2015). This data indicates that on average, nation-wide ambient temperatures vary by more than 50°C in a given year.

In the U.S. distribution environment, packages are likely to encounter a wide variation of temperatures, ranging between -29°C and 49°C. In extreme cases, temperatures as

high as 57°C have been recorded in parked trucks in areas of the Southwestern US (Hannon et al., 1998). A 2001 International Safe Transit Association research project examined summertime temperature and humidity in interstate less-than-truckload (LTL) shipments throughout the Southwestern U.S. This study utilized electronic data recorders to report interior trailer temperatures as high as 60°C. While discrete exposure times to such extremes were limited, the data indicates that interior temperatures of trailers in such settings can consistently exceed those of the surrounding ambient environment (ISTA, 2001).

A one-year study of temperature and humidity in ocean containers monitored port, sea, and rail transport and storage conditions in shipments between Europe, Asia, and North America. This study revealed that temperature differences in a given shipment, while typically very minor at sea, can be extreme in land transport. At the 50th percentile, recorded temperatures ranged from 3°C to 43°C. The highest and lowest temperatures recorded were -21°C and 57°C. Results also revealed that the upper portion of shipping containers exposed to direct sunlight can be over 15°C hotter than the outside environment. Furthermore, the bottom row of boxes within a container can experience temperatures as much as 20°C cooler than the uppermost row (Leinberger, 2006). A container study executed by OsPack and Fosters in 2007 likewise indicated that greater temperature fluctuations are observed on land than on sea. Exposure to sun was found to cause severe temperature increase, with roof temperatures of containers exposed to direct sunlight regularly peaking at 50°C. Temperatures of the exterior metal of containers exposed to direct sunlight can reach 30°C greater than the ambient environment, and interior temperatures can be more than 10°C above ambient (OsPack and Fosters, 2007). Direct solar radiation is cited as the primary cause of temperature variation within shipping containers. While the effect of sun exposure can be mitigated in containers stored below deck during sea transport, solar radiation exposure is frequently inevitable during land transport, often causing interior container temperature up to 30°C higher than ambient environment temperatures (Weiskircher, 2008).

Research presented by Dr. T. Goedecke summarizes temperature fluctuations in freight container shipments between Europe and destinations in Asia and Australia. Tem-

peratures were recorded in the interior trailer environment and in water-filled plastic drums and intermediate bulk containers (IBCs) by means of a 28-channel temperature logger. Air temperatures as high as 48°C were recorded in the freight container, with maximum temperatures in the vapor space of the plastic drums and IBCs reaching 40°C and 37°C, respectively. While continued research is recommended, this data suggests that air temperatures of approximately 50°C in the container and 40°C in the packaging are considered normal conditions of transport for the routes and seasons evaluated (Goedecke, 2008).

2.5 Overview of Polyethylene Foam Cushioning Material

Polyethylene (PE) foam is used ubiquitously in a vast spectrum of applications—including recreational equipment, automotive, and structural engineering—but is most commonly used as a cushioning material in protective packaging systems. PE foam is manufactured worldwide, can be modified to possess specialty characteristics, and is a relatively inexpensive material. As a category, PE foams are light, flexible, resilient, hydrophobic, able to withstand impact, and are available in an array of colors, thicknesses, and densities.

PE foam is formed by mixing a gaseous hydrocarbon blowing agent into a molten polymer in a pressurized environment. This blowing agent vaporizes as the pressure is reduced, and the cooled polymer-gas composite is left with internal cavities, or cells. When the cells are individual, isolated, and not interconnected, as in the case of PE foam, a material is considered closed-cell, Fig. 2.3 (Groover, 2010). PE foam cells are roughly spherical and range in diameter from 1–2.5 mm, with larger cell sizes corresponding to lower density foams. For example, a PE foam sample with a density of 1.5 lb/ft³ will have a cell diameter of about 2.5 mm (Sealed Air Corporation, 2012).

To manufacture extruded PE foam, solid petroleum-derived PE resin is initially melted in a single or twin-screw extruder. Approximately two-thirds of the way up the extruder barrel, a blowing agent (commonly pentane, HFC-152a, carbon dioxide, or a blend) is injected into the melted polymer as a liquid or gas under pressure. Nucleators added in

Figure 2.3: SEM photograph of closed-cell PE.

the extruder provide initiation sites to aid in controlling cell size and uniformity. Commonly used nucleators include talc, citric acid, and citric acid-sodium bicarbonate blends. Additionally, colorant concentrates can also be added to control aesthetic properties (Wagner, 2009). The elevated pressure in the extruder prevents vaporization of the blowing agent until the mixture exits the extruder die. Upon exit from the die, the blowing agent vaporizes as the pressure is reduced, causing rapid expansion of the polymer melt. The cooled polymer-gas composite is closed-cell PE foam. To prevent breakage and inconsistencies in the final melt, cooling must be carefully controlled. To produce PE plank foam, the melt is extruded through a rectangular slit die onto a conveyor belt. Plank-type PE foams typically range from 1–5 in thick and 24–48 in wide (Suh and Tusim, 2009). The resultant plank of PE foam can then be cut and formed to suit a specific application.

Extruded PE foam is most commonly used in protective packaging applications. PE foam possesses many unique properties which make it an excellent packaging material: it is resilient, strong, flexible, lightweight, chemical and moisture resistant, easily formed, and is available in a broad spectrum of densities. Additionally, PE foam is reusable and

recyclable, and can be specially formulated for anti-static, fire-retardant, and UV-resistant characteristics. Single-layer, extruded PE foam planks are often used in packaging for dynamic cushioning. Here, the purpose of the foam is to mitigate the amount of shock transmitted to the product in the situation of a drop, toss, or other impact. Medium density foams are often used for these applications, typically in weights of 1.5–4 lb/ft³. The thickness of foams used for dynamic cushioning normally ranges from 1–5 in, depending on the weight, size, and fragility of the product, as well as the number and height of impacts expected in the distribution stream. PE foam is often configured as a molded corner pad, end-cap, or load separator, and its ability to endure recurrent shocks make it well-suited for securing products through blocking and bracing. PE foam is used commonly as a protective packaging material for valuable, sensitive, or fragile products, as commonly encountered in the electronic, technology, and automotive industries (Sealed Air Corporation, 2009).

Because PE is a semicrystalline polymer, it possesses both a glass transition temperature (T_g) and a melting temperature (T_m). Below T_g , polymers such as PE have limited molecular motion, experience minute changes in volume with fluctuating temperature, and are typically stiff, rigid, and resistant to deformation. Above T_g , polymers have increased molecular motion, are free to reorganize molecules to change volume with changes in temperature, and are pliable. Low-density polyethylene (LDPE) has a T_g of -120°C, meaning that for most practical purposes the material is well above its T_g (Selke et al., 2004). As temperature increases toward T_m (105–115°C for LDPE), molecular motion increases and PE becomes more malleable and less resistant to deformation. Conversely, as the temperature is lowered toward the T_g , PE, while still pliable, becomes stiffer and less malleable (Selke et al., 2004). These temperature-dependent changes intrinsic to PE-based materials likewise affect the stiffness or softness, and thus the mechanical properties, of PE foam.

2.6 Testing of Cushioning Material at Non-Standard Conditions

Limited work has been published in the area of characterizing the shock absorption properties of expanded polymer foam cushion material over a range of temperatures. K. Hatton of San Jose State University performed research to evaluate the effect of temperature on the shock absorption properties of several polymeric cushion materials. In accordance with ASTM D1596, this study utilized a falling guided platen mounted with an accelerometer to measure cushion performance. Three cushion samples were evaluated: expanded polyurethane (EPU), expanded polystyrene (EPS), and expanded polyethylene (EPE). The densities of the three materials tested were 2.2, 1.0, and 1.0 lb/ft³, respectively. Sample dimensions were 8 x 8 in with a thickness of 2 in, and specimens were impacted from an equivalent free fall drop height of 30 in.

Impact testing was performed at five static stresses, and four replicate drops were performed at the three static stresses surrounding the optimal point, the static stress yielding the lowest impact mass acceleration value. This impact testing procedure was performed on sets of each material, conditioned in an environmental chamber at four discrete temperatures: -17, 3, 23, and 43°C. Since the materials evaluated were not hydrophilic, relative humidity was not controlled. To analyze the thermal characteristics of each material, conditioning was monitored using a thermocouple sensor inserted into the center of each cushion block. Temperature readings were recorded for 15 hours at a rate of one data point every 30 minutes, and it was determined that all material samples reached thermal equilibrium with the conditioning chamber environment within two hours. Based on this preliminary study, specimens were impacted within 30 seconds of removal from the conditioning chamber so as to minimize heat exchange with the environment.

This research revealed that temperature had a noticeable effect on the cushioning properties of EPU and EPE, and only a minimal effect on EPS. Cushion curves were constructed for each material at each temperature, and it was determined that for EPE,

increasing temperature caused the static stress yielding the minimum acceleration to decrease. This is analogous to the optimum point shifting in a negative direction on the static stress axis of a cushion curve. Best-fit linear regression was used to develop formulae in attempt to quantify the effect of temperature on cushioning performance. The R-values for the relationships between temperature and static stress were found to be 0.90 and 0.94 for EPE and EPU, respectively, and these models were not experimentally validated (Hatton, 1998).

A continuation of the Hatton study was presented in 2003. The cushioning properties of EPE and EPS were evaluated at four temperatures: -17, 3, 23, and 43°C. The densities of the EPE and EPS were 2.2 and 1.0 lb/ft³, respectively, and the ASTM D1596 method of cushion analysis was utilized. To easily achieve the static stresses necessary for testing, sample sizes of 8 x 8, 7 x 7, 6 x 6, and 4 x 4 in were used, all with a thickness of 2 in. Samples were conditioned to the non-standard environment according to ASTM D4332, and were removed from the chamber and placed on the cushion tester within 30 seconds to avoid heat exchange with the environment. This study revealed that the cushion properties of EPS were minimally influenced by temperature. For EPE, as temperature increased from -17°C to 43°C, the optimum static stress decreased by about 40% for a first impact, 30 in drop (Marcondes et al., 2003).

A 2010 study assessed the effect of temperature and relative humidity on the cushioning characteristics of a biopolymer foam, expanded polylactic acid (EPLA). The ASTM D1596 procedure and the stress-energy method were used to evaluate cushioning properties. Two densities of EPLA were evaluated, 2.7 and 3.2 lb/ft³, and testing was performed at six temperatures: -25, 1, 20, 24, 40, and 59°C. The size of the cushion samples was 3.5 x 3.5 in, and three thicknesses were tested 1, 1.9, and 2.8 in. No statistically significant variation of the stress-energy equation generated from first impact 20 in drop data was observed for either foam density over the range of temperatures tested. The R^2 values obtained ranged from 0.01 to 0.45 and further testing is recommended to quantify the effects of temperature and humidity on the cushioning properties of EPLA (Szymanski, 2010).

Chapter 3

Predicting the Effect of Temperature on the Shock Absorption Properties of Polyethylene Foam

3.1 Abstract

Polyethylene (PE) foam is a material used commonly in protective packaging for its shock absorption properties. When developing a package design intended to mitigate shock to the product, decisions are typically made based on established cushion evaluation procedures performed at standard laboratory conditions. Distribution environment temperatures, however, can vary greatly from the condition at which these materials are assessed. The research presented in this paper utilizes the stress-energy method of cushion evaluation, and highlights temperature-dependent trends in the stress-energy equations of PE foam tested at twelve different temperatures, ranging from -20°C to 50°C . A quadratic polynomial is used to describe the variation in the stress-energy equation coefficients over

the temperature range evaluated. The model developed enables cushion curve prediction for any static stress, drop height, material thickness, and temperature expected over the intended range of use of the material. This model is validated by performing additional impact testing of samples at various temperatures and comparing experimentally obtained acceleration values to those predicted by the model. Further model analysis is performed to estimate the optimal static stress for the material at any temperature within the range tested, and to study the variation with temperature of this optimal point. Results reveal that the model developed is capable of predicting the shock absorption properties of the material within the range of parameters tested, and that the optimal static stress of the material decreases by about 60% as temperature increases from -20°C to 50°C.

3.2 Introduction

A cushion curve is a two-dimensional tool characterizing the shock absorbing properties of a cushion material over a range of static stresses. These curves are often used in the comparison of different materials and even to support cushion system design. Cushion curves are developed for materials at standard laboratory conditions only. These materials are often polymer foams, the mechanical properties of which are known to be temperature dependent. Real world use of these materials is over a wide range of temperatures. Therefore, understanding the effect of temperature on the mechanical performance of polymer foam cushioning material is important to optimum protective packaging design.

Polyethylene (PE) (including PE foam), like all polymers, can undergo significant property changes with variations in temperature. Because PE is a semicrystalline polymer, it possesses both a glass transition temperature (T_g) and a melting temperature (T_m). Below the T_g , polymers such as PE have limited molecular motion, experience minute changes in volume with fluctuating temperature, and are typically stiff and rigid. Above T_g , polymers have increased molecular motion, are free to reorganize molecules to change volume with changes in temperature, and are pliable. PE has a T_g of approximately -120°C, meaning

that for the purpose of this study the material is well above its T_g . As temperature increases toward T_m , molecular motion increases and PE becomes more ductile and less resistant to deformation. Conversely, as the temperature is lowered toward the T_g of PE, the material, while still pliable, becomes stiffer and less malleable (Selke et al., 2004).

Since the mechanical properties of PE are affected by temperature, selection of an appropriate PE-based cushion material for a protective packaging application mandates an understanding of the conditions the packaging system will encounter in the distribution environment. In the contiguous United States, average seasonal temperatures range from about 0°C in January to 23°C in July. Observing regional average minimum and maximum temperature data from 1901 to 2015, temperatures across the contiguous United States typically range from approximately -16°C to 37°C in a given year (National Oceanic and Atmospheric Administration, 2015). This information indicates that on average, nationwide ambient temperatures vary by more than 50°C in a given year. In the United States distribution environment, packages are likely to encounter a wide variation of temperatures, ranging between -29°C and 49°C. Many delivery trucks lack temperature control in the cargo area, and temperatures as high as 57°C have been recorded in parked trucks in areas of the Southwestern U.S. (Hanlon et al., 1998; Boe, 2013). According to prior studies of environmental conditions in shipping containers, temperatures can on average range from 3°C to 42°C, and in extreme cases from -20°C to 50°C (ISTA, 2001; Leinberger, 2006; OsPack and Fosters, 2007; Goedecke, 2008). The broad temperature range encountered in the distribution environment necessitates an evaluation of the performance of polymer foam cushioning materials at the temperatures at which they are used.

Limited work has been published in the area of characterizing shock absorption properties of polymer foams over a range of temperatures. Two widely accepted methods of cushion evaluation are presented in ASTM D1596 and D4168. Both of these standards are used to develop sets of dynamic cushion curves for a specific material. In each method, the variables of impact velocity and static stress are modified to generate cushion curves, which depict graphically the ability of a material to mitigate transmission of shock to a

product. ASTM D1596 - Standard Test Method for Dynamic Shock Cushioning Characteristics of Packaging Material, utilizes a falling guided platen assembly to directly impact a test specimen. An accelerometer fixed to the platen records a shock response, and a cushion curve is created by plotting the platen acceleration over a range of static stresses (platen weight divided by cushion area). Testing is conducted at various drops heights and for various cushion thicknesses to create a family of cushion curves for a given density of material (ASTM, 2014a). In ASTM D4168 - Standard Test Methods for Transmitted Shock Characteristics of Foam-in-Place Cushioning Materials, shock response is measured by way of a user-created foam-in-place package with a dummy block bearing an internally mounted accelerometer. A free fall drop tester or shock machine is utilized to attain the velocity change required to simulate a range of drop heights (ASTM, 2014c).

Both ASTM D1596 and D4168 state that if no other requirements exist, testing should be performed at standard conditions of 23°C and 50% relative humidity. If attempting to evaluate a material at special or non-standard conditions, ASTM designates that conditioning should be performed for a period of time sufficient to achieve and sustain equilibrium of the specimen with the conditioning environment. Furthermore, when testing at special conditions, the specimen should be returned to the conditioning chamber between drops or impacts, and should not be out of the special condition for longer than 30 minutes. Alternatively, both ASTM D1596 and D4168 mention that the test apparatus can be moved into the chamber, where testing can be carried out (ASTM, 2014a,c).

Research presented by Hatton in 1998 assessed the effect of temperature on the shock absorption properties of some polymeric cushion materials. In this study, a falling guided platen (ASTM D1596) was used to evaluate three cushion samples: expanded polyurethane (EPU), expanded polystyrene (EPS), and expanded polyethylene (EPE). The densities of the three materials tested were 2.2, 1.0, and 1.8 lb/ft³, respectively. The samples were impacted from an equivalent free fall drop height of 30 in, and were evaluated at five static stresses, with four replicate drops performed at the three static stresses surrounding the optimal point (the static stress yielding the lowest acceleration response). This impact

testing sequence was performed on sets of each material conditioned at four temperatures: -17, 3, 23, and 43°C. At each temperature, conditioning was monitored using a thermocouple inserted into the center of each block, and temperature readings were recorded for 15 hours at a rate of one data point every 30 minutes. It was determined that all samples reached thermal equilibrium with the conditioning environment within 2 hours. In order to minimize heat exchange with the environment, specimens were impacted within 30 seconds of removal from the chamber. After cushion curves were constructed for all materials and conditions tested, best-fit linear regression was used in an attempt to develop formulae to quantify the effect of temperature on the minimum transmitted acceleration and optimum static stress for each material (Hatton, 1998).

An adjunct of the Hatton study, research by Marcondes et al. published in 2003 evaluated the impact response of EPE and EPS conditioned at -17, 3, 23, and 43°C. To reduce the effect of heat exchange with the environment, samples were impacted within 30 seconds of removal from the chamber. It was found that over the range of temperatures tested, temperature had a negligible effect on the shock absorption properties of EPS. However, for EPE it was shown that as temperature increased from -17 to 43°C, optimal static stress decreased while transmitted acceleration at optimum static stress increased (Marcondes et al., 2003).

Work presented by Szymanski in 2010 evaluated the effect of temperature and relative humidity on the cushion properties of a biopolymer foam, expanded polylactic acid (EPLA). Both ASTM D1596 and the stress-energy method were used to assess cushion properties. Two densities of EPLA, 2.7 and 3.2 lb/ft³, were evaluated after conditioning at each of six temperatures, ranging from -25 to 30°C. Results reflected no statistically significant variation of the shock absorption properties of the EPLA samples at the temperatures and relative humidities tested (Szymanski, 2010).

The research presented in this paper improves upon prior work in the area of polymer foam cushion testing in three distinct ways. Firstly, whereas previous studies evaluated cushion performance at four or six temperatures, this study considers performance at twelve

different temperatures. Secondly, this research relies upon an experimentally validated conditioning procedure that assures the intended cushion sample temperature at the time of testing. Finally, this method offers the ability to predict cushioning properties at temperatures other than those tested. The model developed is analyzed to study the shock absorption behavior of polyethylene foam at various temperatures, specifically the variation with temperature of the optimum performance point. The remainder of the manuscript is organized as follows:

Section 3.3 provides an overview of the material used in this study, including thermal characteristics, stress-strain data, and conditioning procedures.

Section 3.4 presents a model describing the variation with temperature of the stress-energy equation and the experimental identification technique employed.

Section 3.5 highlights the analysis of the model, exploring the variation of cushion curves with temperature, and the variation of the optimum point with temperature.

Section 3.6 provides experimental validation of the model, and discusses limitations of the research presented.

Section 3.7 presents concluding remarks.

3.3 Preliminary Work

3.3.1 Material Selection

The extruded polyethylene foam selected for this study, Ethafoam[®] 150 (manufactured by Sealed Air Corporation), is a closed-cell foam with a published density of 1.5 lb/ft³. Samples of this material were cut into blocks of dimensions 6 x 6 x 2 in. This material was selected because it is used in a variety of protective packaging applications, including electronics, automotive, and consumer goods industries.

3.3.2 Thermal Characterization

Thermal characterization of Ethafoam[®] 150 was performed by inserting thermocouples into a specimen. Thermocouples were used to analyze temperature at two locations: the isometric core of the specimen, Position 1, and a corner, near the intersection of three faces, Position 2, Fig. 3.1.

Figure 3.1: Geometry and position of thermocouples in Ethafoam[®] 150 specimen.

Conditioning temperatures of -20°C and 50°C were selected to represent an extreme low and extreme high temperature corresponding to the expected environment of use. Thermal characterization studies were not performed at intermediate temperatures, as the points evaluated represent a most extreme temperature differential with respect to the laboratory conditions. Specimens were conditioned at -20°C and 50°C in an environmental chamber. Temperatures at Positions 1 and 2 were sampled at a rate of 3.5 Hz. The time for specimens to reach thermal equilibrium with the chamber environment at both conditions was found to be less than 120 minutes. All specimens were therefore conditioned for at least 3 hours to assure thermal equilibrium. Preconditioned specimens were removed from the chamber to the laboratory environment of 23°C and temperature change of the specimens was recorded at a rate of 3.5 Hz. It was determined that within 30 seconds of removal from the -20°C environment, temperatures recorded at Position 2 could increase by more than 25°C , Fig. 3.2a. For specimens conditioned at 50°C , temperatures at Position 2 decreased by more than

10°C within 30 seconds of removal from the chamber, Fig. 3.2b. Based on this study, it was determined that specimens should be placed on the cushion tester and impacted within 5 seconds of removal from the chamber to assure specimen conditions since the cushion tester was not in an environmental chamber. For specimens conditioned in the extreme low and high temperature environments, five seconds outside of the chamber resulted in a Position 2 temperature variation of 5°C and 2°C for the -20°C and 50°C tests respectively. Within the first 5 seconds of removal from the chamber, no measurable variation in temperature at Position 1 was observed for specimens conditioned in either environment.

(a) Thermal characterization of Ethafoam[®] 150 conditioned at -20°C.

(b) Thermal characterization of Ethafoam[®] 150 conditioned at 50°C.

Figure 3.2: Thermal characterization of Ethafoam[®] 150 conditioned at -20°C and 50°C, subjected to 23°C environment.

3.3.3 Stress-Strain Characterization

A Satec T10000 Universal Tester was used to characterize the compressive stress-strain behavior of the material. A strain rate of 0.0039 in/min was used, and testing was carried out to 90% strain. This test was performed to determine the working compressive strain range of the material in a cushioning application, which corresponds to the low and high dynamic energy levels selected for shock testing. ASTM D3575 - Standard Test Methods for Flexible Cellular Materials Made from Olefin Polymers provides a test procedure for compression deflection. This test standard dictates that sufficient force should be used to produce 25% deflection—or strain—over the entire top area of a polymer foam specimen (ASTM, 2014b). The manufacturer of Ethafoam[®] 150 expands upon this information by publishing compression deflection data for Ethafoam[®] 150 at 10, 25, and 50% strain to account for low and high compressive loading of the cushion material (Sealed Air Corporation, 2008). An Olympus i-Speed 3 high-speed camera was used to determine actual deflection of the specimens during cushion testing. The data from the camera was used in analysis to determine what combinations of static stress and drop height were required to produce 10% and 50% deflection of the cushion specimen. Cushion testing was performed with increasing static stress and drop height, and was also recorded with the high-speed camera at a rate of 3000 frames per second. The video obtained was used to measure maximum cushion deflection upon impact, from which the actual strain was calculated. Performing cushion testing with static stress and drop height parameters obtained from the manufacturer's published cushion curves, high-speed video analysis revealed that the intended working range of the material is not 10–50% as initially presumed, but rather was found to be 24–87% strain. The combinations of static stress and drop height required to produce 24% and 87% strain were used as the dynamic energy end points for the range evaluated to produce the stress-energy curve.

3.3.4 Conditioning Procedure

Based on the expected average temperature range in the contiguous United States distribution system, twelve discrete temperatures were selected for preconditioning of specimens. Starting at 5°C and increasing in 5°C increments to 50°C, ten temperatures were selected. The ASTM-specified 23°C was included, as well as an extreme low of -20°C, for a total of twelve temperatures at which specimens were conditioned for cushion testing.

3.4 Model Identification

The stress-energy method of cushion curve determination was used to capture the energy absorption behavior of the cushion material. The upper and lower energy level limits were determined by high-speed video analysis, and two intermediate points were selected for a total of four energy levels, based on prior work (Marcondes, 2007; Marcondes et al., 2008; Daum, 2011a,b; Batt and Paulin, 2012; Paulin, 2012; Paulin et al., 2013). The platen weight and drop height combinations necessary to obtain the selected energy levels were determined, and impact testing of the cushion specimens was performed according to ASTM D1596. At each of the four energy levels, five replicate specimens were tested. The procedure was repeated at each of twelve temperatures for a total of 240 impacts. The resulting dynamic energy and dynamic stress were calculated for each impact and used in the stress-energy method of cushion curve determination (Burgess, 1990, 1994; Daum, 2006, 2008). For each of the twelve data sets obtained through testing at different temperatures, dynamic stress was plotted versus dynamic energy. In this method, an exponential trendline of the form

$$y = Ae^{Bx} \tag{3.1}$$

is fit to a data set at a particular temperature. The dynamic stress and dynamic energy are represented as,

$$y = Gs \quad \text{and} \quad x = \frac{sh}{t} \tag{3.2}$$

respectively, where G is the maximum acceleration of the impacting mass, s is the static stress or w/A (weight / area), h is the equivalent free fall drop height, and t is the specimen thickness. A and B represent the model coefficients identified in the curve fit operation. Figure 3.3 illustrates an example of a stress-energy curve generated for impact data collected at 23°C. Substituting Eqs. (3.2) into Eq. (3.1) and solving for the impact mass acceleration yields

$$G = \frac{Ae^{B\frac{sh}{t}}}{s}. \quad (3.3)$$

Equation (3.3) can then be used to generate cushion curves for any reasonable cushion thickness and equivalent free fall drop height over a range of static stresses. Figure 3.4 illustrates an example of a cushion curve constructed using the A and B coefficients identified in the curve fit in Fig. 3.3 for drop height of 24 in and cushion thickness of 2 in.

Figure 3.3: Dynamic Stress versus Dynamic Energy for Ethafoam® 150 at 23°C.

Figure 3.4: Cushion curve generated from stress-energy equation at 23°C. Drop height: 24 in; cushion thickness: 2 in.

An exponential equation of the form in Eq. (3.1) was fit to each data set corresponding to the twelve test temperatures. The A and B coefficients obtained from the stress-energy equations at each temperature were tabulated and are shown in Tab. 3.1. Sta-

Table 3.1: Stress-energy equation A and B coefficients at twelve test temperatures.

<i>Temperature</i> ($^{\circ}C$)	<i>A</i>	<i>B</i>
-20	17.589	0.055
5	12.308	0.088
10	12.045	0.090
15	11.018	0.097
20	10.031	0.107
23	9.869	0.108
25	9.400	0.111
30	9.130	0.115
35	8.836	0.118
40	8.720	0.121
45	8.269	0.125
50	8.233	0.127

tistical analysis of the variation of the A and B coefficients was performed and a quadratic polynomial was fit to both the A coefficients versus temperature, and the B coefficients versus temperature, yielding

$$A(T) = A_2T^2 + A_1T + A_0$$

and

$$B(T) = B_2T^2 + B_1T + B_0. \quad (3.4)$$

Substituting Eqs. (3.4) into Eq. (3.3) yields

$$G(s, T) = \frac{(A_2T^2 + A_1T + A_0)}{s} e^{\frac{sh}{t} B_2T^2 + B_1T + B_0}. \quad (3.5)$$

The least squared polynomial fits resulted in R^2 values over 0.99 and root mean square error (RMSE) values less than 0.2. Figure 3.5 illustrates both polynomial fits using all twelve temperature data sets, and the polynomial coefficients are listed in Tab. 3.2.

(a) A coefficient versus temperature.

(b) B coefficient versus temperature.

Figure 3.5: Quadratic polynomial model of A and B coefficient versus temperature.

Table 3.2: A and B fit polynomial coefficients.

A_2	0.0017	B_2	$-6E-06$
A_1	0.1852	B_1	0.0013
A_0	13.28	B_0	0.0819

3.5 Model Analysis

The polynomial representation of the stress-energy method exponential coefficients enables study of the behavior of the material over a range of temperatures. The model developed is used to analyze not only the variations in the cushion curves with temperature, but also the shifting of the optimum static stress for a given specimen thickness and drop height.

3.5.1 Variation of Cushion Curves with Temperature

Increasing temperature results in a decrease in the A coefficient and increase in the B coefficient in the stress energy equation, Eq. (3.3). Figure 3.6 demonstrates the individual effect of variation of the A and B coefficients on hypothetical cushion curves generated. As the A coefficient decreases from 12.308 to 9.869 to 8.233 with the B coefficient held constant, the cushion curve maintains its approximate shape and shifts to lower acceleration values over the static stress range observed, Fig. 3.6a. As the B coefficient increases from 0.088 to 0.108 to 0.127 with the A coefficient held constant, the slope steepness of the cushion curve in the high static stress range decreases, Fig. 3.6b.

(a) Effect of variation in A coefficient on cushion curve, with B coefficient held constant.

(b) Effect of variation in B coefficient on cushion curve, with A coefficient held constant.

Figure 3.6: Effects of variations in A and B coefficient on cushion curves.

The degree to which a material deflects under various static stresses defines the "U" shape of a cushion curve, Fig. 3.4. Under low static stresses, there is insufficient weight to cause the cushion to defect, thus acceleration values are high. When subjected to high static stresses, a large deflection occurs and the cushion bottoms out. This bottoming out is associated with a compaction or densification of the material, and results in high acceleration values. The middle region of the cushion curve represents the optimum performance range for the material and the ideal balance between too little and too much dynamic deflection (White et al., 2000; Gibert and Batt, 2015).

To observe the effect of temperature on cushion curves, curves generated from data obtained at three different temperatures, -20, 15, 50°C, are plotted in Fig. 3.7. The characteristic of PE-based materials to become more pliable and more resistant to deformation with increasing temperature is supported by this data (Selke et al., 2004). At low static stresses (0.1–1.0 lb/in²) cushions conditioned at -20°C yield acceleration values higher than those of cushions conditioned at 15°C. This is due to the fact that the increased stiffness and reduced malleability caused by low-temperature conditioning results in less cushion deflection, and thus higher impact mass acceleration. Conversely, at corresponding static stresses, cushions conditioned at 50°C are less resistant to deformation, and therefore deflect more upon impact, yielding lower impact mass acceleration. Observing static stresses above 1.2 lb/in², the increased stiffness from cold-conditioning causes specimens to be more resistant to bottoming out, and thus yield lower acceleration values than 15°C conditioned specimens. In the higher static stress range, cushions conditioned at 50°C yield impact mass acceleration values higher than those of standard-conditioned specimens, because their increased malleability and reduced resistance to deformation causes bottoming out to occur at lower static stresses.

Figure 3.7: Effect of variation in temperature on cushion curves, showing cushion curves at -20°C, 15°C, and 50°C. Drop height: 24 in; cushion thickness: 2 in.

3.5.2 Variation of Optimum Static Stress with Temperature

The optimum static stress for a cushion material at a given drop height and specimen thickness is the static stress that corresponds to the lowest acceleration on the cushion curve. This represents the static stress at which the material dissipates the most energy. Analysis of the model enables the study of the shifting of this optimal point with temperature. The optimum static stress for the cushion curve at each temperature is found by differentiating the identified model, Eq. (3.5), with respect to static stress to obtain the slope, yielding

$$\frac{\partial G(s, T)}{\partial s} = -A(T) \frac{1}{s^2} e^{\frac{B(T)h}{t}s} + \frac{A(T)}{s} \frac{B(T)h}{t} e^{\frac{B(T)h}{t}s}. \quad (3.6)$$

Since the optimum static stress occurs at the minimum where the slope is zero, Eq. (3.6) is set equal to zero and solved using the solve function in MATLAB[®]. The resulting optimum static stress is determined at various temperatures and plotted in Fig. 3.8. Understanding how the optimum static stress of the cushion curves shifts with temperature allows the model developed in the previous section to be used to select the ideal static stress for a particular temperature of use. For the temperature range, drop height, and cushion thickness parameters analyzed, the optimum static stress decreases from 2.1 lb/in² at -20°C to 0.85 lb/in² at 50°C. These results are consistent with materials science principles, which present that as temperature increases from -20°C to 50°C, the material softens and becomes less resistant to deformation. Therefore, the material will begin to bottom out at a lower static stress and, correspondingly, the minimum acceleration will occur at a lower static stress. Figure 3.9 depicts how the impact mass acceleration and the optimum static stress of Ethafoam[®] 150 vary over a reasonable static stress and temperature range.

The model developed in this study improves on previous prediction methods, which rely on best-fit linear regression between temperature and optimum static stress (Hatton, 1998). A previous model, which is based on four data points and has a comparatively low R^2 value of 0.90, indicates that as temperature increases by 10°C, the optimum static stress decreases by approximately 0.09 lb/in². This relationship is depicted as a vector displayed

on acceleration versus static stress axes, which indicates that as temperature increases across the range tested, the optimum static stress decreases (Marcondes et al., 2003). The previous model is limited in that it assumes a purely linear relationship between optimum static stress and temperature, and relies on a small sample size that does not reasonably account for temperatures intermediate to those tested. Furthermore, this model describes only one set of parameters—a drop height of 30 in and a cushion thickness of 2 in—and fails to expand application of this relationship to other drop heights or material thicknesses.

Figure 3.8: Optimum static stress of Ethafoam[®] 150, from -20°C to 50°C.

Figure 3.9: Minimum acceleration and corresponding optimum static stress of Ethafoam[®] 150 from -20°C to 50°C. Drop height: 18 in; cushion thickness: 2 in.

3.6 Model Validation

3.6.1 Experimental Validation of Model

Validation of the model developed in this study was performed by first using the model to predict impact acceleration values at temperatures not originally used in defining the model. Impact data collected at these temperatures per the ASTM D1596 procedure was then compared to the predicted values.

The quadratic polynomials capturing the variation of the A and B coefficients, Eqs. (3.4), were refit to shock performance data collected at a minimal number of temperatures. This was done to simulate how one might use this model to characterize the performance of a material over a wide range of temperatures. Four temperatures were used instead of the twelve temperatures used to characterize the shape of the curve in the previous section. The shock performance of the material was measured at the typical 23°C and at the extreme high and low temperatures of interest (-20°C, 50°C), with data collected at one additional intermediate temperature, 40°C. The A and B coefficient polynomials from the refit are listed in Tab. 3.3. The refit models yielded R^2 values over 0.99 and root mean square error (RMSE) values less than 0.2.

Table 3.3: A and B fit polynomial coefficients of refit four-point model.

A_2	0.0017	B_2	$-6E-06$
A_1	0.1852	B_1	0.0013
A_0	13.28	B_0	0.0819

The validation phase observes data collected at temperatures not used in the refitting of the model. Data collected at several temperature, static stress, and drop height combinations was compared to the acceleration values predicted by the 4-point model. Each experimental acceleration value represents the mean of five replicates tested at that static stress and drop height combination. Experimental acceleration values, predicted acceleration values, and percent difference are presented in Tab. 3.4. This data is presented

visually in Fig. 3.10, Fig. 3.11, Fig. 3.12, and Fig. 3.13. The error bars of the experimental acceleration data represent the standard deviation of the five replicate drops performed at the corresponding parameters. The error bars of the predicted acceleration data represent the 18% between laboratory reproducibility standard deviation specified in ASTM D1596 (ASTM, 2014a).

The experimental acceleration values obtained from testing performed at the three lower energy levels (static stress and drop height combinations) fall within 17% of the acceleration values predicted by the 4-point model. This indicates that the model is capable of predicting cushion performance in compliance with the between laboratory reproducibility outlined in ASTM D1596 (ASTM, 2014a). At the highest energy level tested, percent differences between experimental and predicted acceleration values range from 24–44%, Fig. 3.10, Fig. 3.11, Fig. 3.12, and Fig. 3.13. As dynamic energy increases, the dispersion of dynamic stress values increases. This is evident in comparing on the 5°C stress-energy plot the spread of the five points collected at the 2.1 lb/in² dynamic energy level to that at the 21.8 lb/in² dynamic energy level, Fig. 3.14. The trend of greater dispersion of data points with increasing dynamic energy is even more prominent at higher temperatures, Fig. 3.15. Additionally, comparison of stress-energy data at 5°C and 45°C, Fig. 3.14, Fig. 3.15, shows that the dispersion of data at a given dynamic energy level becomes greater as temperature increases from 5°C and 45°C.

These observations are consistent with prior analyses of the stress-energy method (Marcondes et al., 2008; Daum, 2011a; Paulin et al., 2013), which indicate that the spread of data collected increases with increasing dynamic energy, with the largest dispersion observed at the highest energy level. This is reflected in the highest of the four energy levels yielding the largest percent differences in each data set. Results also revealed that dispersion increases with increasing temperature. Thus, the most significant percent difference between the experimental and predicted acceleration values was observed at the maximum dynamic energy level at 45°C.

Table 3.4: Experimental and predicted acceleration (4-point model).

Temp	Static Stress	Drop Height	Experimental Acceleration	Predicted Acceleration (4-Point Model)	Percent Difference
°C	lb/in ²	in	g	g	%
5	0.38	12	39.59	39.97	0.96%
	1.08	18	23.86	27.43	13.92%
	1.43	24	34.96	40.41	14.47%
	1.61	30	52.53	67.23	24.54%
10	0.38	12	38.78	37.93	-2.21%
	1.08	18	23.75	27.20	13.53%
	1.43	24	35.55	41.86	16.30%
	1.61	30	53.73	72.59	29.86%
15	0.38	12	34.55	36.08	4.33%
	1.08	18	24.42	26.95	9.83%
	1.43	24	36.60	43.22	16.59%
	1.61	30	55.14	77.87	34.18%
20	0.38	12	30.78	34.43	11.19%
	1.08	18	25.20	26.71	5.82%
	1.43	24	39.22	44.49	12.59%
	1.61	30	57.99	83.08	35.57%
25	0.38	12	28.37	32.99	15.07%
	1.08	18	25.47	26.51	3.99%
	1.43	24	39.57	45.72	14.43%
	1.61	30	60.66	88.23	37.04%
30	0.38	12	27.29	31.78	15.22%
	1.08	18	26.30	26.37	0.27%
	1.43	24	41.27	46.96	12.89%
	1.61	30	63.15	93.38	38.62%
35	0.38	12	25.82	30.81	17.63%
	1.08	18	26.81	26.32	-1.84%
	1.43	24	42.44	48.25	12.81%
	1.61	30	65.84	98.59	39.84%
45	0.38	12	23.91	29.63	21.38%
	1.08	18	27.91	26.58	-4.87%
	1.43	24	44.77	51.18	13.37%
	1.61	30	69.62	109.52	44.55%

Figure 3.10: Experimental and predicted acceleration data, 5°C and 10°C.

Figure 3.11: Experimental and predicted acceleration data, 15°C and 20°C.

Figure 3.12: Experimental and predicted acceleration data, 25°C and 30°C.

Figure 3.13: Experimental and predicted acceleration data, 35°C and 45°C.

Figure 3.14: Dynamic stress versus dynamic energy for Ethafoam[®] 150 at 5°C.

Figure 3.15: Dynamic stress versus dynamic energy for Ethafoam[®] 150 at 45°C.

3.6.2 Limitations of Results

A limitation of this research is that the model presented applies exclusively to Ethafoam[®] 150, and predicts cushion shock absorption properties only over the range of temperatures and static stresses tested. Further study is required to understand the effect of temperature on the shock absorption properties of other polymer foam cushioning materials, such as polystyrene or polypropylene. Further study is likewise necessary to understand the effect of temperature on other densities of PE foam. Alternative materials would yield different predicted A and B coefficients, and thus different stress-energy equations used to generate cushion curves. Additionally, this study is limited to only first impact cushion data. Continued testing is necessary to quantify the effect of temperature on multiple-impact cushion curves.

3.7 Conclusions

In seeking to optimize protective packaging design, this research utilizes the stress-energy method of cushion evaluation to observe temperature dependent trends in the shock absorption properties of polyethylene foam. Observing a temperature range representative of that encountered by a packaging system in the distribution environment, impact testing of PE foam cushions is performed at twelve temperatures ranging from -20°C to 50°C . A quadratic polynomial is developed to describe the variation in the stress-energy equation coefficients of Ethafoam[®] 150 over the temperature range evaluated. The model has an R^2 value over 0.99 and a root mean square error (RMSE) less than 0.2. The model presented enables the generation of cushion curves for any reasonable static stress, drop height, material thickness, and temperature. Further model analysis is performed to identify the static stress yielding minimal impact mass acceleration for a given material thickness and drop height. It is determined that at the parameters tested, as temperature increases from -20°C to 50°C , the optimum static stress of Ethafoam[®] 150 decreases from 2.1 lb/in^2 to 0.85 lb/in^2 . This change is indicative of increasing pliability of the polymeric cushion material

with increasing temperature. Validation is accomplished by comparing impact testing data at selected temperatures to acceleration values predicted by the model. The experimental acceleration values of the three lower energy levels fell within 17% of the predicted values. The percent difference between experimental and predicted data increased with increasing dynamic energy and with temperature, with maximum dynamic energy levels and temperatures yielding the greatest differences of 24–44%. The results of this study led to the following conclusions:

1. The quadratic polynomial developed accurately ($R^2 > 0.99$) describes the variation of the stress-energy model coefficients with temperature.
2. Model analysis reveals that cushion curve variation with temperature complies with materials science principles, which present that polyethylene softens and becomes less resistant to deformation with increases in temperature.
3. Validation indicates that the method developed can be used to predict the effect of temperature on the shock absorption properties of the material. The percent difference between experimental and predicted data increased with increasing dynamic energy and with temperature.

Chapter 4

Conclusions

4.1 Limitations of Results

A limitation of this research is that the model presented applies exclusively to Ethafoam[®] 150, and predicts cushion shock absorption properties only over the range of temperatures and static stresses tested. Further study is required to understand the effect of temperature on the shock absorption properties of other polymer foam cushioning materials, such as polystyrene or polypropylene. Further study is likewise necessary to understand the effect of temperature on other densities of PE foam. Alternative materials would yield different predicted A and B coefficients, and thus different stress-energy equations used to generate cushion curves. A limitation to the method presented in this paper is that more than four data points may be required for a strong understanding of the ideal fit of the model. For example, observing the data collected, fitting of a linear model yields a fairly strong R^2 value of approximately 0.90. A quadratic polynomial model, however, indicates a much stronger fit, with a R^2 value of over 0.99. If developing a model from only four points, a quadratic polynomial fit may not be obvious, and further data collection may be necessary to achieve the most accurate fit. Continued research is recommended to analyze the optimal quantity and range of temperatures at which testing should be performed to understand material performance over a range of temperatures, and further validation of the method is

recommended. This study is limited to only first impact cushion data. Continued testing is necessary to quantify the effect of temperature on multiple-impact cushion curves.

4.2 Conclusions

In seeking to optimize protective packaging design, this research utilizes the stress-energy method of cushion evaluation to observe temperature dependent trends in the shock absorption properties of polyethylene foam. Observing a temperature range representative of that encountered by a packaging system in the distribution environment, impact testing of PE foam cushions is performed at twelve temperatures ranging from -20°C to 50°C . A quadratic polynomial is developed to describe the variation in the stress-energy equation coefficients of Ethafoam[®] 150 over the temperature range evaluated. The model has an R^2 value over 0.99 and a root mean square error (RMSE) less than 0.2. The model presented enables the generation of cushion curves for any reasonable static stress, drop height, material thickness, and temperature. Further model analysis is performed to identify the static stress yielding minimal impact mass acceleration for a given material thickness and drop height. It is determined that at the parameters tested, as temperature increases from -20°C to 50°C , the optimum static stress of Ethafoam[®] 150 decreases from 2.1 lb/in^2 to 0.85 lb/in^2 . This change is indicative of increasing pliability of the polymeric cushion material with increasing temperature. Validation is accomplished by comparing impact testing data at selected temperatures to acceleration values predicted by the model. The experimental acceleration values of the three lower energy levels fell within 17% of the predicted values. The percent difference between experimental and predicted data increased with increasing dynamic energy and with temperature, with maximum dynamic energy levels and temperatures yielding the greatest differences of 24–44%. The results of this study led to the following conclusions:

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Appendices

Appendix A Cushion Specimen Temperature Mapping

A.1 Procedure and Equipment

Thermal characterization of Ethafoam 150[®], Fig. 1, was performed by inserting National Instruments NI 9211 thermocouples, Fig. 2, into a 6 x 6 x 2 in cushion block specimen. Thermocouples were used to analyze temperature at two locations: the isometric core of the specimen, Position 1, and a corner, near the intersection of three faces, Position 2, Fig. 3, Fig. 4. Conditioning temperatures of -20°C and 50°C were selected to represent an extreme low and extreme high temperature corresponding to the expected environment of use. Thermal characterization studies were not performed at intermediate temperatures, as the points evaluated represent a most extreme temperature differential with respect to the laboratory conditions of 23°C. Specimens were conditioned at -20°C and 50°C in a Parameter Generation & Control (PGC) environmental chamber, Fig. 5. Temperatures at Positions 1 and 2 were sampled at a rate of 3.5 Hz. The time for specimens to reach thermal equilibrium with the chamber environment at both conditions was found to be less than 120 minutes. All specimens were therefore conditioned for at least 3 hours to assure thermal equilibrium. Preconditioned specimens were removed from the chamber to the laboratory environment of 23°C and temperature change of the specimens was recorded at a rate of 3.5 Hz.

A.2 Results

It was determined that within 30 seconds of removal from the -20°C environment, temperatures recorded at Position 2 could increase by more than 25°C, Fig. 6. For specimens conditioned at 50°C, temperatures at Position 2 decreased by more than 10°C within 30 seconds of removal from the chamber, Fig. 7. For specimens conditioned in the extreme low and high temperature environments, 5 seconds outside of the chamber resulted in a Position 2 temperature variation of 5°C and 2°C for the -20°C and 50°C tests respectively. Within the first 5 seconds of removal from the chamber, no measurable variation in temperature at

Position 1 was observed for specimens conditioned in either environment.

Figure 1: Ethafoam[®] specimen.

Figure 2: National Instruments NI 9211 thermocouple unit.

Figure 3: Schematic of thermocouple position in Ethafoam[®] specimen.

Figure 4: Photo of thermocouple placement in Ethafoam[®] specimen.

Figure 5: PGC environmental conditioning chamber.

Figure 6: Thermal characterization of Ethafoam[®] 150 conditioned at -20°C.

Figure 7: Thermal characterization of Ethafoam[®] 150 conditioned at 50°C.

Appendix B Analysis of Minimum and Maximum Energy Levels

B.1 Stress-Strain Analysis

A Satec T10000 Universal Tester was used to characterize the stress-strain behavior of Ethafoam[®] 150. A strain rate of 0.0039 in/min was used, and testing was carried out to 90% strain, Fig. 8. Resulting stress versus strain was plotted, Fig. 9. This phase

Figure 8: Ethafoam[®] 150 in Satec at 0% strain (left) and 90% strain (right).

of the study was performed to determine the compressive working range of the material. ASTM D3575 - Standard Test Methods for Flexible Cellular Materials Made from Olefin Polymers provides a test procedure for compression deflection. This test standard dictates that sufficient force should be used to produce 25% deflection—or strain—over the entire top area of a polymer foam specimen (ASTM, 2014b). The manufacturer of Ethafoam[®] 150 expands upon this information by publishing compression deflection data for Ethafoam[®] 150 at 10, 25, and 50% strain to account for low and high compressive loading of the cushion material (Sealed Air Corporation, 2008).

Figure 9: Stress-strain plot of Ethafoam® 150. Strain rate: 0.10 mm/min.

An Olympus i-Speed 3 high-speed camera, Fig. 10, was used to determine actual deflection of the specimens during cushion testing. Figure 11 depicts the recording setup. The intended use of the camera was to analyze what combination of static stress and drop height was required to produce 10% and 50% deflection of the cushion specimen. Cushion testing was performed on a Lansmont falling guided platen assembly, Fig. 12, beginning at the lowest reasonable static stress and drop height, about 0.2 lb/ft² and 12 in, according to the manufacturer's published cushion curves. Testing was continued out to a static stress of approximately 2.0 lb/ft² and a drop height of 30 in. Cushion testing was recored at a rate of 3000 frames per second. The video obtained was used to measure maximum cushion deflection upon impact, from which the actual strain was calculated using

$$\%strain = \frac{d}{t} \quad (1)$$

where d is deflection of the cushion specimen recorded by the high-speed camera, and t is the pre-impact thickness of the cushion specimen. High-speed video analysis revealed

that impact testing at the reasonable minimum and maximum static stress and drop height parameters indicated by the manufacturer's published cushion curves yields percent strain values very different from the 10-50% expected based on the published compression deflection data.

Figure 10: Olympus i-Speed 3 high-speed camera.

Figure 11: Olympus i-Speed 3 recording setup.

Figure 12: Lansmont falling guided platen cushion tester.

The reasonable working range of the material, rather than the 10-50% initially presumed, was found to be 24-87% strain, Fig. 13. At the minimum intended static stress and drop height indicated by the manufacturer's published cushion curves, Ethafoam[®] 150 deflects by about 24% of the original specimen thickness. On the high static stress and drop height end of the working range of the material, it was revealed that Ethafoam[®] 150 experiences 87% deflection, or strain.

B.2 Energy Levels and Resulting Strain Levels

The minimum and maximum strain of the material correspond to the dynamic energy endpoints of the exponential curve used in the stress-energy method. Dynamic energy, x , is defined as

$$x = \frac{sh}{t} \quad (2)$$

where s is the static stress or w/A (weight / area), h is the equivalent free fall drop height, and t is the specimen thickness. The static stresses and drop heights needed to achieve these energy endpoints were calculated, and two intermediate endpoints were selected for a total of four energy levels. These energy levels, along with corresponding static stresses, drop heights, and average percent strain, are presented in Tab. 1.

Figure 13: Expected and actual working strain range of Ethafoam[®] 150.

Table 1: Energy levels tested, and corresponding static stresses, drop heights, and resulting strain.

<i>Energy Level (lb/in²)</i>	<i>Static Stress (lb/in²)</i>	<i>Drop Height (in)</i>	<i>Avg. % Strain</i>
2.1	12	0.38	24
8.8	18	1.08	63
15.5	24	1.43	79
21.8	30	1.61	87

Appendix C Dynamic Stress Versus Dynamic Energy Plots

From the data obtained in the impact testing phase, dynamic energy and dynamic stress were calculated for each impact. Dynamic stress was plotted versus dynamic energy, and an exponential curve was fit to the data set. The equation of this line is the stress-energy equation for the material tested. For each of the twelve data sets obtained through testing at different temperatures, dynamic stress was plotted versus dynamic energy. An exponential equation was fit to each data set corresponding to the twelve test temperatures, shown below. The A and B coefficients obtained from the stress-energy equations at each temperature were tabulated and are shown in Tab. 2.

Table 2: Stress-energy equation A and B coefficients at twelve test temperatures.

<i>Temperature ($^{\circ}C$)</i>	<i>A</i>	<i>B</i>
-20	17.589	0.055
5	12.308	0.088
10	12.045	0.090
15	11.018	0.097
20	10.031	0.107
23	9.869	0.108
25	9.400	0.111
30	9.130	0.115
35	8.836	0.118
40	8.720	0.121
45	8.269	0.125
50	8.233	0.127

Figure 14: Dynamic stress versus dynamic energy for Ethafoam® 150 at -20°C.

Figure 15: Dynamic stress versus dynamic energy for Ethafoam® 150 at 5°C.

Figure 16: Dynamic stress versus dynamic energy for Ethafoam[®] 150 at 10°C.

Figure 17: Dynamic stress versus dynamic energy for Ethafoam[®] 150 at 15°C.

Figure 18: Dynamic stress versus dynamic energy for Ethafoam[®] 150 at 20°C.

Figure 19: Dynamic stress versus dynamic energy for Ethafoam[®] 150 at 23°C.

Figure 20: Dynamic stress versus dynamic energy for Ethafoam[®] 150 at 25°C.

Figure 21: Dynamic stress versus dynamic energy for Ethafoam[®] 150 at 30°C.

Figure 22: Dynamic stress versus dynamic energy for Ethafoam® 150 at 35°C.

Figure 23: Dynamic stress versus dynamic energy for Ethafoam® 150 at 40°C.

Figure 24: Dynamic stress versus dynamic energy for Ethafoam[®] 150 at 45°C.

Figure 25: Dynamic stress versus dynamic energy for Ethafoam[®] 150 at 50°C.

Appendix D Statistical Analysis of Stress-Energy Equation Coefficients by Temperature Fit Models

Statistical analysis of the A and B coefficient variation over the twelve temperatures was performed. A quadratic polynomial was fit to both the twelve A coefficients versus temperature, Fig. 26, and the twelve B coefficients versus temperature, Fig. 27. These equations are referred to as the 12-point models. The bivariate fits of A and B by temperature yielded R^2 values over 0.99 and root mean square error (RMSE) values less than 0.2. The polynomial coefficients are listed in Tab. 3.

Table 3: A and B fit 12-point polynomial model coefficients.

A_2	0.0017	B_2	$-6E - 06$
A_1	-0.1852	B_1	0.0013
A_0	13.28	B_0	0.0819

In the validation phase, quadratic polynomials capturing the variation of the A and B coefficients were refit to shock performance data collected at four temperatures, Fig. 28, Fig. 29. The bivariate refits of the four A coefficients and four B coefficients by temperature yielded R^2 values over 0.99 and root mean square error (RMSE) values less than 0.2. The A and B coefficient polynomials from the refit are listed in Tab. 4.

Table 4: A and B fit 4-point polynomial model coefficients.

A_2	0.0017	B_2	$-8E - 06$
A_1	-0.1831	B_1	0.0013
A_0	13.25	B_0	0.0835

Figure 26: Bivariate fit of A coefficient by temperature (°C), 12-Point Model.

Figure 27: Bivariate fit of B coefficient by temperature ($^{\circ}\text{C}$), 12-Point Model.

Figure 28: Bivariate fit of A coefficient by temperature (°C), 4-Point Model.

Figure 29: Bivariate fit of B coefficient by temperature (°C), 4-Point Model.

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