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Demonstration of Packaging Materials Alternatives to Expanded Polystyrene

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DEMONSTRATION OF PACKAGING MATERIALS ALTERNATIVES TO EXPANDED POLYSTYRENE

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FOREWORD

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory is the Agency's center for investigation of technological and management approaches for reducing risks from threats to human health and the environment. The focus of the Laboratory's research program is on methods for the prevention and control of pollution to air, land, water and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites and ground water; and prevention and control of indoor air pollution. The goal of this research effort is to catalyze development and implementation of innovative, cost-effective environmental technologies; develop scientific and engineering information needed by EPA to support regulatory and policy decisions; and provide technical support and information transfer to ensure effective implementation of environmental regulations and strategies.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available the EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

E Timothy Oppelt, Director
National Risk Management Research Laboratory

ABSTRACT

Widespread use of toxic chemicals in all segments of industry and commerce has created the need to deal with burgeoning waste streams containing toxic chemicals emitted into the air and water and buried in the soil. Two decades of pollution control regulations have not been completely effective in reducing environmental releases of toxic chemicals, nor in mitigating the human health effects from toxic chemical use. The United States Environmental Protection Agency's 33/50 Program is one example of a new generation program that focus directly on pollution prevention to reduce toxic chemical releases. The 33/50 Program encourages industry to enter voluntary agreements to reduce emissions of 17 toxic chemicals.

This report represents the second demonstration of cleaner technologies to support the goals of the 33/50 Program under the EPA Cooperative Agreement No. CR821848. The report presents assessment results of alternative packaging materials which could potentially replace expanded polystyrene in consumer product packaging applications. By replacing EPS with alternative packaging materials, the use and potential emissions of 33/50 chemicals could be reduced. The assessment evaluated the technical (i.e., performance), environmental, and economic characteristics of EPS and three alternative packaging materials: starch-based foam plank, layered corrugated pads, and recycled polyethylene foam.

The results of the technical evaluation reveal the strengths and weaknesses of each protective packaging material. Under standard temperature and humidity conditions, dynamic drop test results reveal that layered corrugated pads offer as much single-impact protection as EPS at a material thickness of 1.5 inches. For samples of identical thickness, starch-based foam and recycled polyethylene foam display a greater ability to absorb energy resulting from multiple impacts, when compared to EPS. Finally, prototype designs using layered corrugated pads and starch-based foam protect a tested consumer electronic product to a level comparable to that of EPS.

To capture the full impact of package manufacturing, and the release of 33/50 chemicals, a life-cycle perspective was employed to evaluate the environmental impacts of each material. The release of 33/50 chemicals predominate the pre-manufacturing life-cycle stage. Benzene emissions to air and water dominate this life-cycle stage for EPS; for starch-based foam planks, the use of agricultural chemicals for the production of corn results in the use and potential release of cyanide and other 33/50 chemical; few, if any, 33/50 chemical releases are expected from pre-manufacturing for layered corrugated pads when manufactured from 100 percent recycled materials. Within the package manufacturing life-cycle stage, VOC emissions dominate the EPS process, while energy consumption dominates starch-based foam plank. Finally, each material had waste management options, each of which represent options to minimize landfill disposal. Preferred waste management options are presented for each material.

To complete the evaluation of alternative packaging materials, an economic evaluation was performed on the prototype packaging designs developed for the tested consumer electronic product. Within this identical packaging application, assuming all other parameters are equivalent, layered corrugated pads were the most cost competitive packaging alternative when compared to EPS. Though 37 percent more expensive than EPS, layered corrugated pads were more cost competitive than starch-based foam. Similar cost comparisons were not available for recycled PE foam.

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CONVERSION TABLE

Units:	Multiply by:	To get:
British Thermal Units (BTU)	1.054	kilo-Joules (kJ)
	2.93×10^{-4}	kiloWatt-hours (kW-hr)
feet (ft)	0.3048	meters (m)
cubic feet (ft^3)	0.028	cubic meters (m^3)
inches (in)	0.0254	meters (m)
pounds (lb)	0.4536	kilograms (kg)
pound per square inch (lb/in^2)	703.1	kilograms per square meter (kg/m^2)
	6.895	kilo-Pascals (kPa)
square feet (ft^2)	0.0929	square meters (m^2)
square inches (in^2)	6.45×10^{-4}	square meters (m^2)
°C = 0.56 x °F - 17.78		

ACKNOWLEDGMENT

The Center for Clean Products and Clean Technologies acknowledges the time and resources offered by the following organizations and individuals.

- Philips Consumer Electronics: Without their laboratory resources and professional expertise, the goals and objectives of the study would not have been achieved. Special thanks goes to Robert S. Gepp, Staff Engineer, who developed the dynamic drop test apparatus used in the study and offered his technical guidance throughout the project.

- The various package manufacturers: They supplied material samples and developed prototype designs, all of which were tested within this project. Special recognition goes to Tuscarora (Greenville, TN), Menasha Sus-Rap Corporation (Danville, VA), and American Excelsior (Memphis, TN and Arlington, TX).

- Dr. Raymond Krieg, University of Tennessee Mechanical Engineering Department, and his mechanical engineering students who performed static, stress-strain, and creep tests on selected packaging materials.

- Dr. John R. Mount, Food Science and Technical University, and the University of Tennessee Food Science Lab which supplied the apparatus used to perform the static, stress-strain tests of the study.

Without their cooperation and support, the results of this study would not have been possible.

CHAPTER 1

INTRODUCTION

The hazardous waste problem and many of the persistent air and water pollution problems are primarily toxic chemical problems. Widespread use of toxic chemicals in all segments of industry and commerce has created the need to deal with burgeoning waste streams containing toxic chemicals emitted into the air and water and buried in the soil. Two decades of pollution control regulations have not been completely effective in reducing environmental releases of toxic chemicals. Nor have regulations always protected workers from the effects of toxic chemicals used in the workplace or consumers from the effects of toxic chemicals found in consumer products. However, a new generation of programs and policies have emerged which have a greater potential to reduce toxic chemical releases. The United States Environmental Protection Agency's (EPA) 33/50 Program is one such new-generation program.

33/50 PROGRAM

The 33/50 Program was a voluntary pollution prevention initiative to reduce national releases and off-site transfers to the environment of 17 toxic chemicals. The Program asked industry to voluntarily develop their own reduction goals that contribute toward national reduction goals of 33 percent by the end of 1992 and 50 percent by the end of 1995. Reductions were measured against a 1989 baseline of information reported to EPA under the Toxic Release Inventory (TRI). The 17 chemicals or chemical groups included in the 33/50 Program are as follows:

- Benzene
- Cadmium and Cadmium Compounds
- Carbon Tetrachloride (CTC)
- Chloroform (CFM)
- Chromium and Chromium Compounds
- Cyanide and Cyanide Compounds
- Lead and Lead Compounds
- Mercury and Mercury Compounds
- Methylene Chloride (DCM)
- Methyl Ethyl Ketone (MEK)
- Methyl Isobutyl Ketone (MIBK)
- Nickel and Nickel Compounds
- Tetrachloroethylene (PCE)
- 1,1,1-Trichloroethane (TCA)
- Toluene
- Trichloroethylene (TCE)
- Xylene

EPA selected these compounds for the voluntary pollution prevention initiative based on a number of factors including their high production volumes, high releases and off-site transfers relative to their production, opportunities for pollution prevention, and their potential for causing human health and environmental effects.[1]

EPA's National Risk Management Research Laboratory (hereafter NRMRL, formerly Risk Reduction Engineering Laboratory) has funded research in support of the 33/50 Program. The goal of the NRMRL-funded research is to evaluate the performance and cost of pollution prevention options and to disseminate that information through reports, technical meetings, seminars, and other media. While this research was originally funded by NRMRL to support the 33/50 Program, the technologies that will be evaluated have a broad range of applications within industry. This should offer pollution prevention benefits beyond the reduction of national pollution releases and off-site transfers of the 33/50 chemicals.

OBJECTIVES OF THIS RESEARCH

The "Cleaner Technology Demonstrations for the 33/50 Chemicals" project is a cooperative agreement between the EPA-NRMRL and the Center for Clean Products and Clean Technologies (hereafter Center) funded by NRMRL in support of the 33/50 Program. The overall objective of this project is to demonstrate substitutes for the 33/50 chemicals in order to encourage reductions in their use and release. For the substitutes that will be evaluated, this study has objectives in the areas of technical, environmental, economic, and national impact evaluations. The following are the specific objectives in each area:

1. Technical evaluation
   - evaluate the effect of the substitute(s) on process and product performance as compared to the 33/50 chemical(s)
2. Environmental evaluation
   - evaluate the potential for reduction in releases and off-site transfers of the 33/50 chemical(s) in the production process or product stage in which the 33/50 chemicals are used and released
   - compare the overall life-cycle environmental attributes of the 33/50 chemicals and the substitute(s) for the same use
3. Economic evaluation
   - evaluate the total cost of the substitute(s) as compared to the 33/50 chemical(s)
4. National environmental impact evaluation
   - evaluate the environmental impact of replacing the 33/50 chemical(s) with the substitute(s) on a national scale

The subjects of the demonstration projects were selected from seven priority use clusters of the 33/50 chemicals identified in *The Product Side of Pollution Prevention: Evaluating the Potential for Safe Substitutes*.[2] The seven priority use clusters are shown in Table 1. Primary use clusters are defined as those products and/or processes that consume a significant portion (weight fraction) of the 33/50 chemicals. *The Product Side of Pollution Prevention: Evaluating the Potential for Safe Substitutes* used chemical use trees as the analytical tool to evaluate the priority use clusters of the 33/50 chemicals. Examples of chemical use trees can be found throughout that document.

TABLE 1 - PRIORITY USES OF THE 33/50 CHEMICALS		
Priority Use Cluster	33/50 Chemicals	Function
batteries	Cd, Hg, Ni, Pb Hg	electrodes additive
metal finishing	Cd, Cr, Ni cyanide compounds	metal plates plating path chemicals
plastics and resins	benzene, toluene, xylene Cd, Cr	chemical intermediates stabilizers
paints and coatings	toluene, xylene, MEK, MIBK Cd, Cr, Pb benzene, toluene, cyanides	solvents pigments intermediates of paint resins
degreasing	TCA, TCE, PCE (CFCs), DCM	solvents
dry cleaning	PCE, TCA	solvents
paint stripping	DCM	solvents

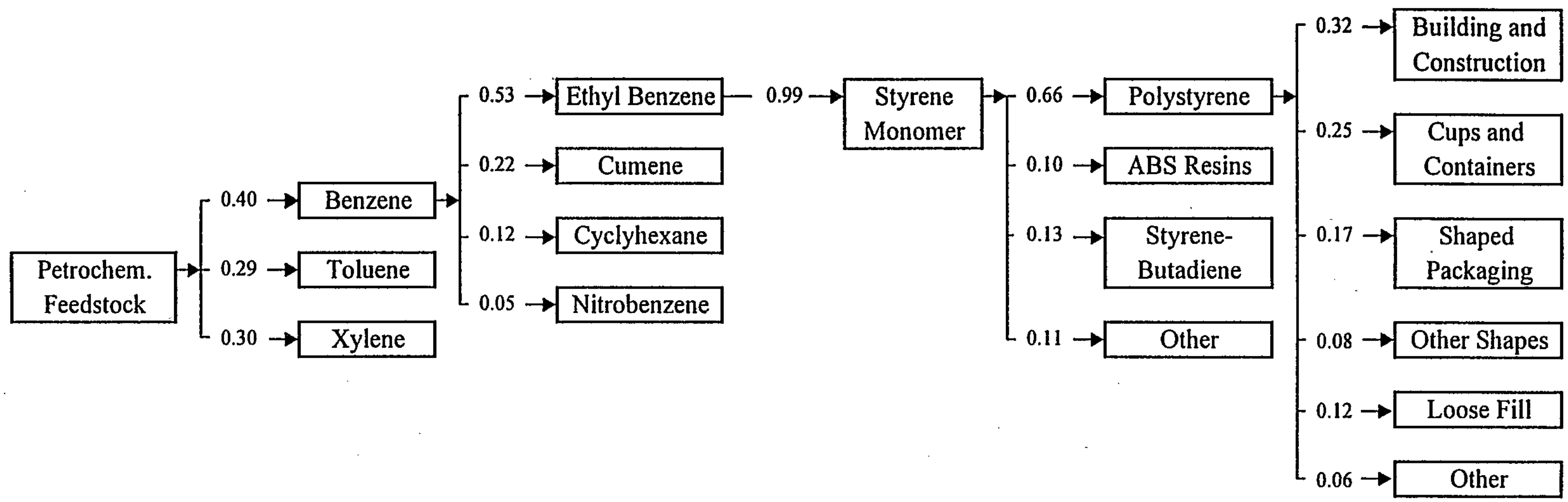
Source: U.S. Environmental Protection Agency. *The Product Side of Pollution Prevention: Evaluating the Potential for Safe Substitutes*. September 1994. EPA/600/R-94/178.

Key:
Cd - cadmium
CFCs - chlorofluorocarbons
Cr - chromium
DCM - methylene chloride
Hg - mercury
MEK - methyl ethyl ketone
MIBK - methyl isobutyl ketone
Ni - nickel
Pb - lead
PCE - tetrachloroethylene
TCA - 1,1,1-trichloroethane
TCE - trichloroethylene

This report represents the second demonstration project to be completed under the EPA-NRMRL project. The first demonstration project focused on substitutes for solvent degreasing processes that eliminate the use of chlorinated organic chemicals; results of this research are presented in *Demonstration of Alternative Cleaning Systems*.[3] This second demonstration project evaluates alternatives to expanded polystyrene (hereafter EPS) as a cushioning material in consumer and industrial packaging. EPS is an example of the priority use cluster "plastics and resins," and is produced from raw materials derived solely from the 33/50 chemical benzene, as the chemical use tree presents in Figure 1.

Three 'alternative' cushioning materials were identified for evaluation within this research: starch-based foam planks, layered corrugated pads, and recycled polyethylene foam. Some of these materials have been used as cushioning materials for some time (corrugated and polyproethylene); others are just now entering the market and identifying/establishing viable applications. These materials are termed 'alternative' because each offers unique features beyond their cushioning capabilities. These unique features include their manufacture from recycled materials, biodegradability, water solubility, recyclability, and reusability. These features as well as the use of 33/50 chemicals are assessed and presented within the context of the evaluations in this project.

FIGURE 1 - CHEMICAL USE TREE FOR BENZENE



Source: U.S. Environmental Protection Agency. *The Product Side of Pollution Prevention: Evaluating the Potential for Safe Substitutes.* September 1994. EPA/600/R-24/178.

Note: Polystyrene products identified in final column represent only expanded polystyrene products.

The goal of this research was to present information on the environmental, economical, and performance characteristics of alternative packaging materials. This information could be used by industry, manufacturers, researchers, and consumers to advance the application of alternative cushioning materials. To accomplish this goal, technical, environmental, and economic evaluations were completed to assess various characteristics and parameters concerning the production, use, and disposal of the cushioning materials. The properties and cushioning characteristics of EPS represent the baseline for this research; evaluation results for each material are compared against those of EPS. A variety of data was required to perform these evaluations, a brief description of which is presented below.

Technical Data

Technical data, specifically the cushioning performance/capabilities of each material, were generated by four separate laboratory test series. Three test series evaluate the general cushioning characteristics of each material using square test samples. These test series included dynamic drop tests, static stress-strain tests, and creep tests. The fourth laboratory test applied selected cushioning materials to a consumer or industry product packaging application. Products were provided by industry partners and packaged in prototype designs developed by the vendors of the selected alternative cushioning materials. These prototype package-product systems were then subjected to a series of performance tests based on industry partner specifications or established International Safe Transit Association test procedures. A discussion of the laboratory procedures and the test results are presented in Chapter 4.

Environmental Data

The environmental evaluation applies a life-cycle perspective to the production, use, and disposal of each of the cushioning materials. With this perspective, quantitative and qualitative data was used to assess and compare the environmental burdens of each packaging material. The data required to complete this evaluation were obtained from a variety of sources. From each material supplier, primary data were collected through questionnaires and site visits for the cushioning material's manufacturing processes. The questionnaires were distributed by mail and completed by the contacts established in each manufacturing facility. Site visits arranged with each contact allowed Center staff to become familiar with the manufacturing processes and ask specific questions to complete and clarify questionnaire responses. Additional data to establish the remaining life-cycles stages of each material were gathered from publicly available data. Examples of such data include the TRI database, published life-cycle assessments, and government surveys. Results from this evaluation are presented in Chapter 5, Environmental Evaluation.

Economic Data

Finally, a quantitative and qualitative economic assessment of each material was performed to fulfill the goals of the economic evaluation. Utilizing the prototype demonstration results, a quantitative evaluation of the equivalent use of each alternative material, as compared to the current EPS application, was determined. Based on this information and the production rate of each industry partner, estimates of packaging production and supply costs were given by each material supplier. Economic considerations that were evaluated on a more qualitative basis include the possible rates of production and the ability to incorporate the alternative material into an existing packaging production line. The details of this evaluation are presented in Chapter 6.

CHAPTER 2

PACKAGING INDUSTRY

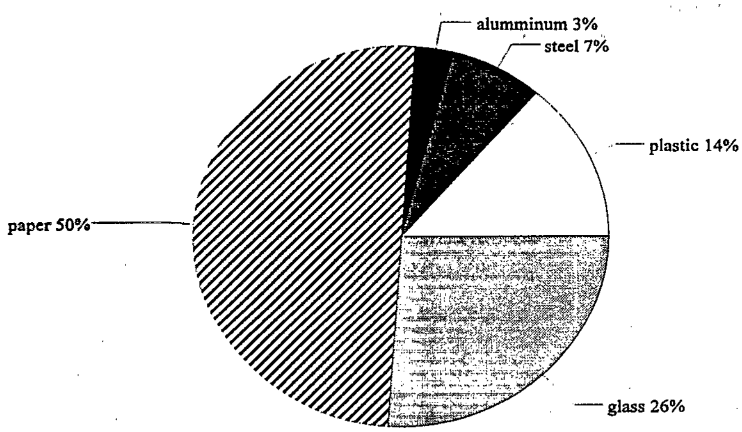
Packaging is viewed by many consumers merely as a means of containing a product. The function of a package, however, is much more extensive. "It is art and science; it is materials and equipment; it is protection, promotion, law, logistics, manufacturing, and materials handling all rolled into one."[4] Packaging has many faces. In its familiar forms it is the box on the shelf at the grocery store and the wrapper on the candy bar. It can also be the crate around a piece of industrial machinery or a bulk container for chemicals (e.g., 250 gallon tote). A package is a process of getting products from the source of production to the point of use in the most beneficial and cost effective manner. To support our current system of production and distribution, packaging, with its many functions, is essential.

HISTORY OF PACKAGING

By the end of the 19th century the Industrial Revolution had created a high level of productivity and inexpensive means of mass transportation for moving products long distances to the customer. Customers were able to pick and choose from a variety of competing products. In this buyer's market, the customer began to demand more for the money, including better product protection (i.e., undamaged, unadulterated, uncontaminated products). With greater affluence, consumers began accepting packaging as a convenience to be discarded without thought. Initially viewed as a necessary evil, packaging became a means by which a manufactured product could be marketed and sold.[5]

Unit packaging was the result of the demands for protection and convenience. By the late 1970's, however, the characteristics of unit packaging which offered the benefits of protection and convenience became an environmental issue as landfill space became limited and resource depletion became an international issue. In 1986, packaging waste accounted for approximately 34 percent (by volume) of the U.S. municipal solid waste stream.[6] This packaging waste was composed of paper (approximately 50 percent by weight), glass (26 percent), plastic (14 percent), steel (7 percent), and aluminum (3 percent); this distribution is presented in Figure 2.[7] The demand for protection and convenience was joined by the demand for more environmentally benign packaging materials and packaging designs. Recycled content, recyclability, and reusability are of interest to the consumer.

FIGURE 2 - BREAKDOWN OF PACKAGING WASTE IN MUNICIPAL SOLID WASTE
(by weight)



MARKET FOR PACKAGING AND PACKAGING MATERIALS

The market for packaging in the United States totals approximately $100 billion annually (up from $25 billion in 1974)[8], representing only 1.4 percent of the $7 trillion United States economy.[9] This expenditure calculates to an average of $400 per year per person (i.e., man, woman, and child) in this country. Worldwide, packaging expenditures total approximately $350 billion, or $70 per person per year.[10] The significance of these figures is subject to interpretation. Some argue that the consumption patterns of the United States are excessive; others argue that our economy, and even the advancement of civilization, cannot develop without packaging.[11]

Over the years, the relative market share for different types of packaging materials has shifted. Plastics sales have continued to grow since the 1950's, while the market share held by paper and paperboard has fluctuated. These figures are reflected in Table 2 which presents consumption rates by material within the packaging market.

TABLE 2 - CONSUMPTION PATTERNS FOR VARIOUS PACKAGING MATERIALS (million lb)

	1991	1993	1995
Plastics in Packaging[1]	16,568	19,569	NA
Expanded Polystyrene[2]			730
Low Density Polyethylene[2]			7,252
Paper and Paperboard[1]	4,560	4,508	NA
Starch-Based Loose-Fill[3]	0	4	8

Sources:
[1] United Nations Secretariat. *1993 Industrial Commodity Statistics Yearbook: Production and Consumption Statistics*. 1996.
[2] *Modern Plastics*. January 1992, 1994, 1996.
[3] Starch-based loose-fill packaging material was introduced in 1990. Consumption figures were estimated as a percentage of loose-fill polystyrene. Starch-based foam plank was introduced in 1996.
NA: Not available.

REGULATIONS EFFECTING THE PACKAGING INDUSTRY

In recent years, packaging legislation has been introduced and enacted at all levels of government: state, federal, and international. At the state level, 2,000 solid waste bills were introduced, with 300 of them specifically addressing packaging issues.[12] The types of legislative initiatives which address the environmental impacts of packaging include resource reduction measures, measures encouraging or mandating recyclability of products, deposit fees, and variable garbage collection fees. Though not legislative in nature, an example of a regional initiative is that of the Council of North Eastern Governors Resource Reduction Task Force. The Task Force has recommended, among other actions, the adoption of preferred packaging guidelines.

At the federal and international level, the German Ordinance for the Avoidance of Packaging Waste (1991) is an example of an ambitious and far-reaching legislative initiative. In short, this Ordinance requires manufacturers to reuse packaging or bear the costs of having it recycled (i.e., if the manufacturer made it, the manufacturer is responsible for it throughout its life cycle).[13] Similar legislation has been implemented in The Netherlands, France, the United Kingdom, Australia, and the European Union.

CHAPTER 3

PACKAGING DESIGN AND CUSHIONING MATERIALS

A package designer must develop effective and economical package-product systems. Effective packaging offers the protection, convenience, and possibly environmental attributes expected by the consumer. Among other factors, the economics of packaging may be affected by material costs, as determined by the product and material markets and demands for the product manufactured, as well as the packaging material bulk and weight which affect the costs of transport. With a knowledge of the physical world (i.e., physical properties of the product and packaging) the designer is able to develop a functional and effective package-product system. The implementation of this package-product system, however, is determined by cost and other considerations within the economic world. Therefore, the designer is constrained by both the physical world and the economic world, and a balance must be established between them.[14] "The ultimate design of a package is a choice which represents the distillation of a multitude of lesser decisions, each relating to a specific package or product requirement as defined by management, marketing, sales, manufacturing, or research and development. Each of these groups approaches the subject from a different viewpoint, yet makes an important contribution to the whole."[15]

PACKAGING DESIGN

Nine steps have been identified and defined for the packaging development pathway.[16] These nine steps, identified in Figure 3, combine and balance the physical and economic worlds mentioned above. The technical evaluation of this research incorporates aspects of Steps 1, 2, 3, 5, and 8; Steps 3 and 4 are considered by the environmental evaluation; and the economic evaluation addresses Steps 4, 5, 6, 7, and 8.

FIGURE 3 - NINE STEPS IN PACKAGING DEVELOPMENT PATHWAY

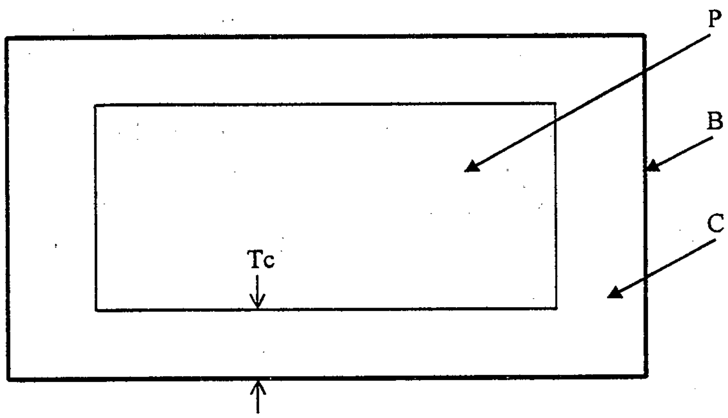
Step #1	definition of product properties as they relate to the package technical requirements
2	definition of package technical and functional properties
3	definition of package styling and design requirements
4	identification of legal or other restrictions/requirements
5	selection of possible package designs and materials
6	estimation of probable cost of development
7	decision whether to proceed
8	package preparation and testing for performance
9	decision whether to proceed for market test

Source: Griffin, Roger C. and Stanley Scharow. *Principals of Package Development.* The AVI Publication Company, Inc., Westport, CT. 1972.

CUSHIONING DESIGN CONSIDERATIONS

Cushioning systems (the material and its designed configuration) are incorporated in package-product systems to protect fragile items. Figure 4 illustrates a basic package-product system which incorporates a cushioning system. The product, which is to be protected from damage, is denoted 'P' in the figure. The container system, comprised on a rigid outer container (denoted 'B') and cushioning material (denoted 'C'), encase the product.

FIGURE 4 - BASIC PACKAGE-PRODUCT SYSTEM



Key: P = product
B = rigid outer container
C = cushioning material
Tc = thickness of cushioning material

When a package-product system, such as that shown in Figure 4, is dropped on a non-resilient, rigid surface, the outer container can impact the surface with considerable force. The cushioning material acts as a buffer between this force and the fragile product; the product does not stop as abruptly as the outer container and the force experienced by the product is reduced. Since any outer container can be devised to encase the cushioning system and product, the crucial factors which must be considered in a cushioning system design are the cushioning material, its thickness (denoted Tc in the figure), and its configuration.[17]

From this description of cushioning design, the nine steps for packaging design can be conveniently reduced to four basic considerations when testing and designing cushioning materials and systems. These four basic considerations are as follows[18]:

- Fragility level.
- Distribution environment (e.g., drop height, temperature, and time).
- Impact shock.
- Cushioning configuration.

Fragility

In order to decide what protective properties a package must have, it is first necessary to know the properties of the product it is to contain. Manufacturers typically know the integrity of their product(s), and therefore have some measure of its fragility level. Fragility is expressed as the maximum G-forces a product or component can experience without resultant damage. G-force is expressed as a dimensionless ratio of the maximum acceleration that an item can safely withstand to the acceleration due to gravity. If susceptible components of a product are inseparable from the rest of the product, the package-product system (i.e., cushioning system) must be designed to protect the most fragile component; for example, a consumer electronic such as a VCR or television, or a glass object such as a vase or bottle. For the subject of this research project, the focus was a consumer electronic product (i.e., VCR) with some fragility level that must be protected. In a VCR, the plastic case may be able to withstand a greater impact force, greater than an unsupported internal electronic piece such as a circuit board. How a package designer uses this measure of fragility is discussed in the prototype demonstration section of Chapter 4, Technical Evaluation.

Distribution Environment

The distribution environment within which a package-product system must travel can significantly influence the design of a cushioning system. The drop height, for example, is defined as the free fall distance a package-product system may drop resulting in an impact velocity and calculated impact force. The drop height is dictated, in part, by the package-product system itself. A light weight object can be thrown like a baseball; thus, the potential drop height to which the package-product system could be subjected may be significant. As the package-product system increases in weight, the drop height decreases. Various standard methods prescribe worst-case potential drop height based on the weight of the package-product system. The highest drop height is typically 30 inches for light weight objects, while for heavy objects (over 250 lb) the potential drop height is reduced to 9 inches.[19] Temperature, humidity, and storage time are other distribution considerations that must be defined and addressed when a cushioning system is designed. The technical evaluation of Chapter 4 evaluates a finite array of distribution environments and their effect on cushioning materials.

Impact Shock

The dynamic laboratory test series completed within the context of the technical evaluation addresses the issue of impact shock. Shock can be described as a disturbance produced by a suddenly applied force in the form of a complex pulse. To evaluate a cushioning material's response to varying shock pulses, a series of static loads are dropped onto material samples from a standard drop height. Expressed as either a single-event impact shock pulse as a function of time, or as a dynamic cushioning curve, the results of drop tests offer a concise and consistent representation of cushioning material properties that aid the packaging designer. The generation, integration, and use of drop test results and dynamic cushioning curves are explained further in Chapter 4, Technical Evaluation.

Cushioning Configuration

Cushioning configuration can be considered the engineered shape of the cushioning material in a specific package-product application. Configuration addresses the thickness, contours, fins, etc. which optimize cushioning ability while minimizing the thickness and quantity of material used (therefore optimizing cost). A cushioning system can be designed as corner pads, end caps, engineered or convoluted pads, etc. The material suppliers of selected cushioning materials incorporate configuration into the design of a prototype packaging system for a specific consumer/industrial product application. In the prototype cushioning design, the three previously defined considerations are incorporated. Knowledge of the product's fragility, the drop height from which it could potentially be dropped, and the cushioning properties of the materials must all be known to design an effective packaging system. How these considerations are used to design a cushioning system is explained in more detail under the prototype evaluation of the Technical Evaluation, Chapter 4.

Though included in the nine design steps for packaging, regulations have been left out of these four considerations for cushioning design. Regulations, as presented above, may place additional restrictions on the design process and must be considered by the packaging designer. Environmental regulations are only one set of regulations that may be applied to packaging. In this study an entire chapter is devoted to economics and the costs and benefits incurred by applying an alternative packaging material to consumer or industrial product packaging. Furthermore, environmental issues including regulations are covered in Chapter 5, Environmental Evaluation.

CUSHIONING MATERIALS

As previously stated, this research evaluated four cushioning materials. EPS was considered the 'typical' cushioning material used in consumer product applications, and represents the baseline against which the other materials are compared. The remaining cushioning materials; starch-based planks, layered corrugated pads, and recycled polyethylene foam, represent alternative cushioning materials which could replace EPS in current industrial and commercial applications. Each material is described in detail below.

Expanded Polystyrene

In 1931 Dow Chemical Company developed and marketed the first extruded polystyrene foam known as Styrofoam®. It is the oldest synthetic and one of the best known cellular plastics. EPS offers many properties desirable in a packaging material; for example, EPS is light weight, has a high strength-to-weight ratio, low moisture absorption, little or no odor, low toxicity, and has good insulating properties. In 1965 EPS was the most widely accepted foamed plastic material used for cushioning. Today, EPS is one of three foamed plastics (along with polyethylene and polyurethane) that dominate cushioning applications.

Philips Consumer Electronics (hereafter Philips) was the primary industry partner in this demonstration project. Philips utilizes EPS as protective packaging material in most national and international consumer product packing applications. With a goal of demonstrating an alternative cushioning material in one of Philip's many applications, the Center adopted many of the packaging criteria implemented at Philips for this research. One primary criterion adopted was the allowable thickness of the cushioning material; all material samples to be evaluated were to have a thickness of 1.5 inches. This criterion was used to maintain the distribution efficiency (termed "cubic efficiency") established by Philips for all products. EPS samples of this thickness were obtained from Tuscarora, Philips' sole supplier of cushioning material in Tennessee.

Starch-Based Foam Planks

In November 1990, American Excelsior began to market its starch-based loose fill cushioning material as an alternative to polystyrene "peanuts." Viewed by many manufacturers and consumers as an environmentally superior packaging alternative, EcoFoam has gained an increasing market share since its introduction. Using this trend, and to expand into additional markets, American Excelsior began to develop and market "Shapes and Sheets," a starch-based foam sheet which could be manufactured into cushioning pads. Within the time frame of this study, the Shapes and Sheets product evolved into the current American Excelsior product EcoPlank - a standard 2 inch plank composed of layers of corrugated starch-based foamed sheets bound together with a water-soluble, starch-based adhesive. EcoPlank represents a biodegradable and water-soluble cushioning product manufactured from a renewable natural resource. American Excelsior manufactured EcoPlank at a thickness of 1.5 inches for this study.

Layered Corrugated Pads

Layered corrugated pads are not new to the packaging market as a cushioning material. In the early 1950's corrugated boxes were a primary source of protective (i.e., cushioning) packaging, and in the 1970's the Forest Products Laboratory, under the direction of the U.S. Department of Agriculture, systematically tested various layered corrugated pads for their cushioning properties and possible applications. Due to advances in the plastics industry and the low cost of plastics, however, the application of layered corrugated pads has been limited.

Menasha Corporation's Sus-Rap Division supplied the Center with flat, 1.5 inch thick layered corrugated pads composed of 100 percent recycled, 26 pound kraft paper for this study. The Sus-Rap Division, located in Danville, Virginia, is part of Menasha Corporation's Material Handling Group. Manufactured from single-faced corrugated sheets bonded together by a water-soluble starch-based adhesive, these corrugated pads offer a product which is composed of recycled material and is recyclable in any corrugated recycle program. Menasha manufactures and markets pads, angles, corners, and troughs to a variety of consumer product manufacturers (e.g., furniture manufacturers).

Molded pulp and honeycomb products are examples of paper and paperboard protective packaging materials, but they were not evaluated in this project due to budget and time constraints.

Recycled Polyethylene Foam

As mentioned above, polyethylene foam has been one of three dominant polymeric materials utilized as a cushioning material in packaging applications. For this study, polyethylene foam was selected to represent a cushioning material that is reusable due to its strength and resilience. If designed into a reusable/returnable container system, polyethylene foam can offer significant economic and environmental advantages which will be discussed in this report. Furthermore, recycled polyethylene foam (hereafter recycled PE foam) is manufactured from recycled material and is recyclable itself. Typically manufactured as a 2 inch plank, the Center received recycled polyethylene foam from the Stephen Gould Corporation (a packaging design consulting firm) in a thickness of 1.5 inches to maintain a consistent evaluation. PE foam is manufactured throughout the United States from either virgin resin or a combination of virgin and recycled resin. AVI Foam, in Arlington, Texas was the particular supplier in the Southeast with which the Center worked during this project.

CHAPTER 4

TECHNICAL EVALUATION

The objective of the technical evaluation was to assess various cushioning properties of each of the four packaging materials. Three separate tests comprise the technical evaluation of this research. Two laboratory test series were performed to evaluate the physical properties of each cushioning material. Dynamic drop tests were used to assess cushioning characteristics; static compression tests were performed to evaluate relationship between stress and strain independent of material size or shape; and creep tests were conducted to determine material deformation under extended periods of stress. The fourth and final test series, prototype demonstrations, evaluated the use of selected cushioning material in specific product packaging applications.

Positive characteristics of each cushioning material were revealed by the results of the technical evaluation. EPS and layered corrugated pads offered the greatest protection from single-event shock impacts. However, the protection offered by layered corrugated pads decreases significantly following repeated impacts. Starch-based foam plank and recycled PE form out-perform EPS in multiple impact tests, showing the least deterioration of cushioning potential even after five dynamic shock impacts. These and other results are presented below. Raw data supporting these results are published separately and can be obtained from the U.S. EPA.

DYNAMIC DROP TESTS

The cushioning capabilities of a packaging material are traditionally presented by dynamic cushioning curves.[20] A dynamic cushioning curve is a graphic representation of dynamic shock cushioning offered by a cushioning material over a variety of static load conditions. Figure 5 presents an example of the dynamic cushioning curves which are used to market a cushioning material. The vertical axis, G-force, is the dimensionless ratio between an acceleration in length-per-time-squared units and the acceleration of gravity in the same units. The horizontal axis, static load (stress), is the applied mass divided by the area to which the mass is applied. A different curve is required for each drop height, material thickness, and type of material. Typically, multiple curves are displayed on the same graph depicting different material thicknesses at one drop height.

To generate a dynamic cushioning curve, a series of drop tests must be performed. These tests involve dropping a specified static load, from a specified height (i.e., free fall drop height), onto a material sample of set dimensions (i.e., surface area and thickness). The acceleration of the mass is monitored over time, and the force imposed on the sample materials by the falling weight, expressed as G-force, is calculated from the acceleration data. A plot of G-force versus time, depicted in Figure 6, is the result of the analysis of a single drop test. The maximum G-force experienced by the sample materials, circled in Figure 6, represents a single data point for a specified static load on the dynamic cushioning curve. A series of drop tests which vary the static load (keeping drop height and material sample dimensions constant) will generate the needed data to create dynamic cushioning curves for a material of a specified thickness.

FIGURE 5 - DYNAMIC CUSHIONING CURVES

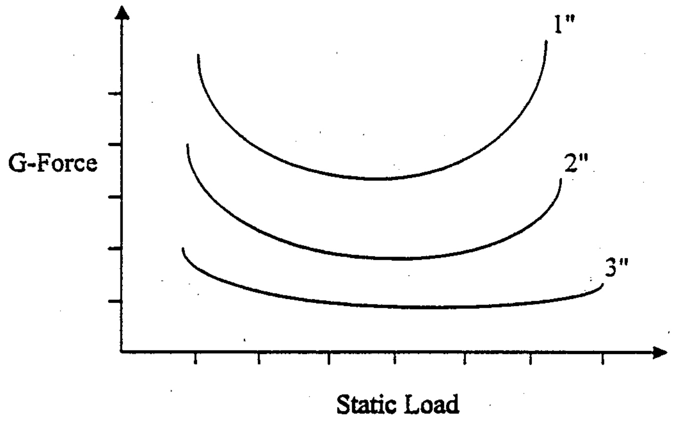
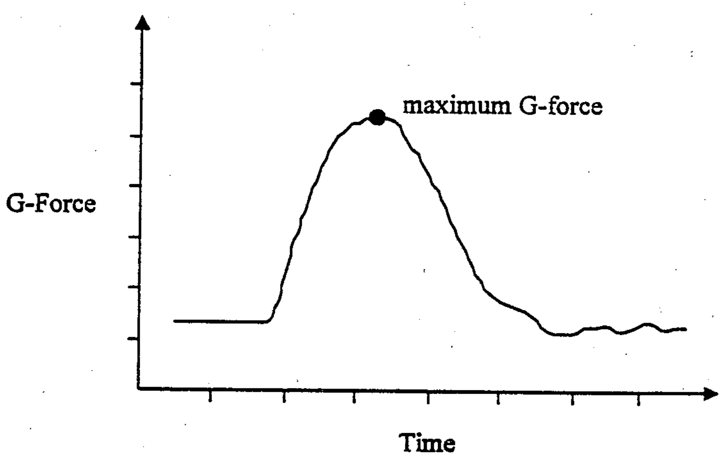


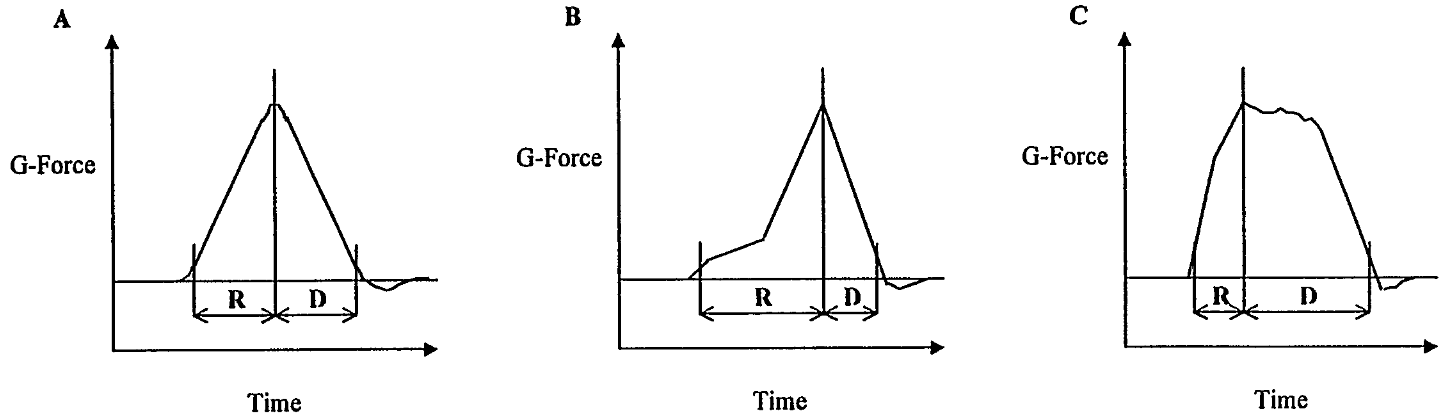
FIGURE 6 - RESULTS OF A SINGLE DROP TEST (DYNAMIC SHOCK)



Note: A typical acceleration-time curve generated by a dynamic drop test is not as smooth as the curve presented here. To eliminate the "noise" experienced and introduced by the recording instruments, apparatus, and packaging system, the curve data is filtered at a level no lower that 10 times the basic pulse frequency.

The curve for a single drop test can offer additional information regarding the general properties of the cushioning material. An optimally loaded cushion will have rise time to and decay time from the maximum force that are approximately equal in duration. If the cushion is overloaded, the rise time becomes substantially greater than the decay time. Most of the static load's impact duration time was spent during deflection (bottoming) of the cushion, resulting in a high deceleration rate. If the rise time of the pulse is substantially less than the decay time, generally the cushion is under-loaded. That is, the cushioning material is too stiff and does not deflect the static load during impact. Figures 7A, 7B, and 7C shows each of the loading conditions. In each case the vertical axis is G-force, the horizontal axis is time, "R" represents rise time, and "D" represents decay time.[21]

FIGURES 7A, 7B, and 7C - INTERPRETATION OF SINGLE DYNAMIC DROP TEST CURVES



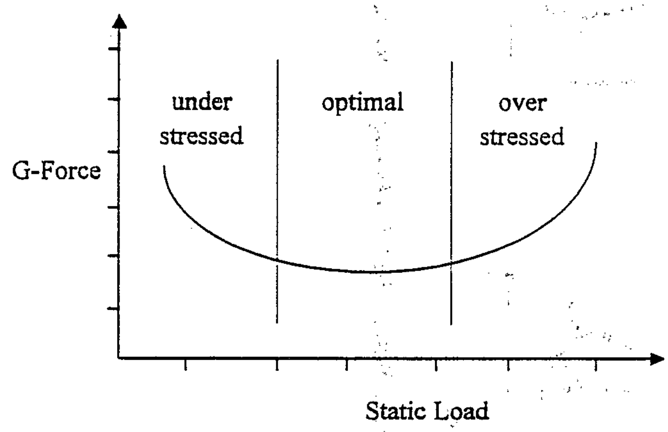
Source: Schueneman, Herbert H. "Packaging Drop Testing: What Is the Data Really Telling Us?" *Packaging Technology and Engineering*. April 1995.

Key:
- R = rise time
- D = decay time

Curve:
- A = Optimally Loaded Cushion
- B = Over-Loaded Cushion
- C = Under-Loaded Cushion

Similarly, three regions can be generally identified in a dynamic cushioning curve: the under-stressed region, the over-stressed region, and the optimal region. These regions are depicted in Figure 8. The optimal region includes the lowest resultant force for that material and its tested configuration (e.g., thickness, contours). A packaging designer thus designs a cushioning system within this region. This design procedure is explained later within this chapter.

FIGURE 8 - THREE REGIONS OF A DYNAMIC CUSHIONING CURVE

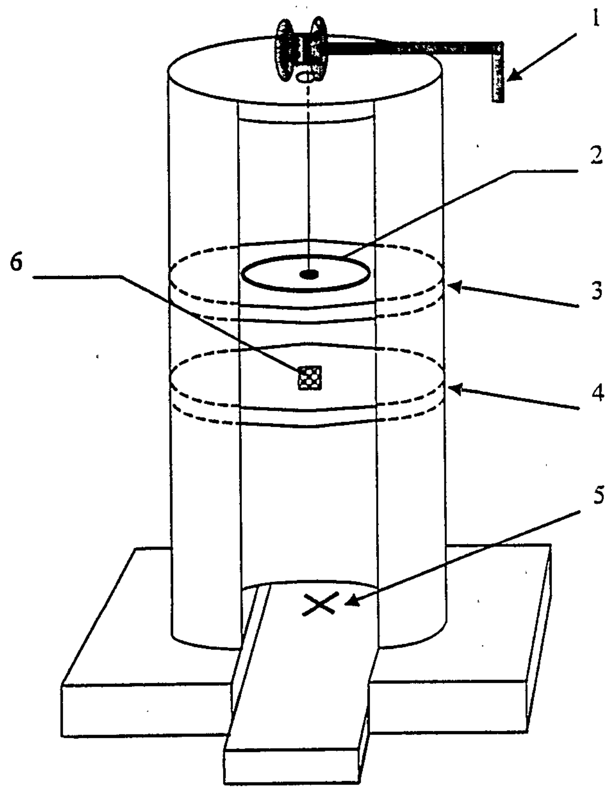


Apparatus

The apparatus used to perform the dynamic drop tests was designed and constructed by the packaging engineers of Philips. Schematically represented in Figure 9, the primary components of the apparatus include a static-load platen, pneumatic-suction platen, and a Endevco Model 7267A Tri-Axial Piesoresistive Accelerometer (i.e., transducer) coupled to a computerized data acquisition system. Transducer details are presented in Appendix A.

Both platens move freely up and down three tightly strung steel guide-wires mounted within the frame of the apparatus. Various static loads can be mounted to the bottom of the static-load platen with three nut-and-bolt pairs. To the top of this platen is mounted the transducer with double-sided masking tape. The pneumatic-suction platen can be raised and lowered by a hand-operated winch. When mounted to a compressed air source, the pneumatic-suction platen grabs the static-load platen and the system is raised to the desired height via this winch. Material samples are mounted on a sample platform with double-sided masking tape, and the platform is slid into position directly under the static-load platen. By closing the compressed air valve, the static-load platen drops, impacting the material sample. The transducer, in turn, records the acceleration-time history of the drop test and displays the shock pulse on the computer screen.

FIGURE 9 - SCHEMATIC DIAGRAM OF DYNAMIC DROP TEST APPARATUS



1 winch
2 compressed air source
3 pneumatic-suction platen
4 static-load platen
5 sample location on platform
6 transducer connected to computer data acquisition system

Procedure

The procedure followed for the dynamic drop test laboratory experiments was from the American Society for Testing and Materials (hereafter ASTM) Standard Method D 1598-91, Standard Test Methods for Dynamic Shock Cushioning Characteristics of Packaging Material. A detailed, step-by-step description of this procedure can be found in Appendix B. Information pertinent to the results of the tests series is discussed below.

A series of six static loads were used to generate the dynamic cushioning curves for each of the materials; starting at 8 lb, the weight of the static-load platen was increased by 5 lb increments to an upper limit of 33 lb. The static load was dropped onto material samples from a drop height of 30 inches. Following the ASTM methodology, each material sample was subjected to a maximum of five consecutive drops at the same static load with an interval of at least one minute between drops.[1] Three sample replicates at each static load increment were performed for each alternative material; two sample replicates at each static load increment were performed for EPS samples. Fewer replicates for EPS were required due to its well defined cushioning characteristics and consistency between samples; similar data were not available for the alternative materials.

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[1] At high static loads, some material samples could not absorb five consecutive drops. The series was discontinued after a G-force which exceeded the transducer setting was experienced.

All acceleration-time histories were recorded for each drop series. The first-drop peak G-force for each replicate was filtered at 200 MHz (i.e., no lower than 10 times the basic pulse frequency, following Philips' and other packaging expert procedures) to eliminate 'noise.' Replicate values were then averaged and recorded for use in the dynamic cushioning curves presented below. If the standard deviation of these filtered and averaged data was greater than 10 percent of the average, one additional sample was tested and included in the average calculation (as specified in the Quality Assurance Project Plan).

Three separate environmental conditions were tested during the dynamic drop test series. Samples stored in an office environment (average temperature was 22 °C; average relative humidity was 51 percent) represented 'standard' conditions. Samples were also tested under desert and tropical environmental conditions. Temperature and humidity for these samples were based on ASTM methodology D 4332-89, Standard Practice for Conditioning Containers, Packages, or Packaging Components for Testing. These conditions are as follows:

- Desert conditions: 60 °C and 15 percent relative humidity
  extremely high heat and low humidity
- Tropical conditions: 40 °C and 85 percent relative humidity[2]
  high heat and extremely high humidity

Using a temperature controlled chamber at Philips, material samples were conditioned under these environments for at least 72 hours before test runs. Dynamic drop tests were performed on these conditioned samples by taking one sample from the chamber at a time, leaving the remaining samples under the extreme conditions.

Dynamic Drop Test Results

Standard Conditions. Following the procedures presented above and in Appendix B, dynamic cushioning curves were generated for six different materials: EPS; low- and high-density layered corrugated pads; low- and high-density starch-based planks; and recycled PE foam. Based on material sample size (6 x 6 inch square), the weights of the static-load platen resulted in a range of static loads from 0.23 lb/sq inch to 0.93 lb/sq inch for recycled PE foam, starch-based planks, and corrugated pads. The EPS samples, which were 4 x 4 inch square, experienced a static load range of 0.50 lb/sq inch to 2.12 lb/sq inch.

Figures 10, 11, 12, and 13 show typical single-event impact shock response curves for each material at optimal static load conditions. Each of these curves have been filtered at 200 MHz. From the theoretical discussion above, a number of observations can be made from these curves.

1. Both representative curves of EPS and recycled PE foam reveal a shape characteristic of an optimally loaded sample discussed in Figure 7A. The rise time to and decay time from the peak G-force are nearly identical. Each single-event shock impact response curve for these materials revealed such a shape. The response curve for recycled PE foam,

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[2] The environmental conditioning chamber utilized for the extreme conditions was not properly operating during the tropical test conditions. Though it was set for a relative humidity of 85 percent, monitoring revealed an average relative humidity of 91 percent.

however, is more symmetrical. The rise and decay times for recycled PE foam (Figure 11) are within 4 percent of each other, while for EPS the rise time is more than 14 percent greater than the decay-time (Figure 10).

2. The curve for the starch-based planks, Figure 12, shows the greatest symmetry and may represent the most optimally loaded sample. However, the peak G-force recorded for this drop is high (in comparison to the other curves), and the rise time and decay time slopes are quite steep. A wider, more sloping bell-shaped curve is considered more optimal; energy is dissipated over a greater time period with less maximum force experienced.
3. Finally, Figure 13 shows the characteristic shock impact response curve for the layered corrugated pads. Resembling that of an under-loaded material, all first-drop impact response curves for the corrugated samples displayed a shape such as this. One possible interpretation of this shape is that the individual layers of fluted material resist collapse up to a certain force (steep rise time slope), then subside layer by layer under a critical force until the impact has been absorbed (the jagged, flat top). The rise time slope is very steep until sufficient force is reached to cause the initial layer of fluted material to give way. A cascade effect of subsiding layers results until the energy of the static load is absorbed and the decay time slope occurs.

Figures 14, 15, 16, and 17 represent dynamic cushioning curves for each of the four cushioning material types. For the purpose of comparison, each of the alternative material cushioning curves is plotted against that of EPS. Further interpretation of each dynamic cushioning curve follows each plot. For supporting data and calculations, the reader should request the separate supplemental report from the U.S. EPA. Table 3, which follows the discussion of each cushioning curve, summarizes the optimal static load and corresponding G-force for each material.

As seen by the dynamic cushioning curve of Figure 14, EPS exhibits the typical 'U-shape' published for most cushioning materials. From this shape, the optimal static load around which a packaging engineer should design is 0.82 lb/sq inch, which has a corresponding G-force of approximately 51. To the left of this optimal region, the curve is rather flat revealing good protective properties even outside the optimal region. To the right, as the load continues to increase; the EPS sample can no longer absorb the energy of the static load thus resulting in a G-force that rises quickly.

Figure 15 compares the dynamic cushioning curves of recycled PE foam and EPS. The first obvious difference between both curves is the optimal region. The optimal region for the recycled PE foam is at a static load of 0.37 lb/sq inch, nearly one-third of that of EPS. Though not much of the recycled PE foam curve extends to the left of this optimal region, to the right the increase in G-forces experienced by the pad is not as great as that for EPS. For recycled PE foam, the static load increased by nearly 300 percent, while the G-force increased by less than 25 percent. This is compared to the G-force experienced by EPS which increases nearly linearly with static load (a two-fold increase in static load doubles the experienced G-force). This suggests that a PE cushion that may be under designed may still perform at the desired level. The optimal static load for recycled PE foam has a corresponding G-force of 55.

Figure 16 presents the dynamic cushioning curve of two types of starch-based planks: low-density and high-density. As the baseline, EPS is represented as a dashed line. At the time this project was initiated, American Excelsior was marketing only the low-density planks. As the technology developed and the market was assessed, American Excelsior began to manufacture a high-density plank as well. At this time, only the high-density plank is considered the EcoPlank product marketed by American Excelsior. The shape of each starch-based material's cushioning curve is nearly identical, with the only difference being their vertical positioning, or the G-force corresponding to the optimal static load region. For low-density starch-based planks the optimal static load is 0.64 lb/sq inch with a corresponding G-force of 65.6; high-density starch-based planks had the same optimal static load with a corresponding G-force of 72. These optimal G-force values are considerably higher than that of EPS.

Figure 17 presents the results for a low-density and high-density layered corrugated pad, and compares them to the baseline EPS dynamic cushioning curve. The most intriguing feature of this plot is that the G-force corresponding to the optimal static load for the low-density corrugated material is lower than that of the EPS; specifically, 46 at an optimal static load of 0.52 lb/sq inch, while for EPS the G-force is 51 at an optimal static load of 0.82 lb/sq inch. Theoretically, this means that a flat pad of layered corrugated can protect a more fragile object as well as a flat pad of EPS. Another unique feature of this plot is that the dynamic cushioning curve for the high-density corrugated material, though starting extremely high, approaches the optimal region of EPS as the static load increases. Low-density pads represent Menasha Sus-Raps' standard product; the high-density material was included in this study for completeness, to expand the knowledge of the material, and to determine possible applications.

FIGURE 10 - TYPICAL RESPONSE OF EPS TO SINGLE-EVENT IMPACT SHOCK

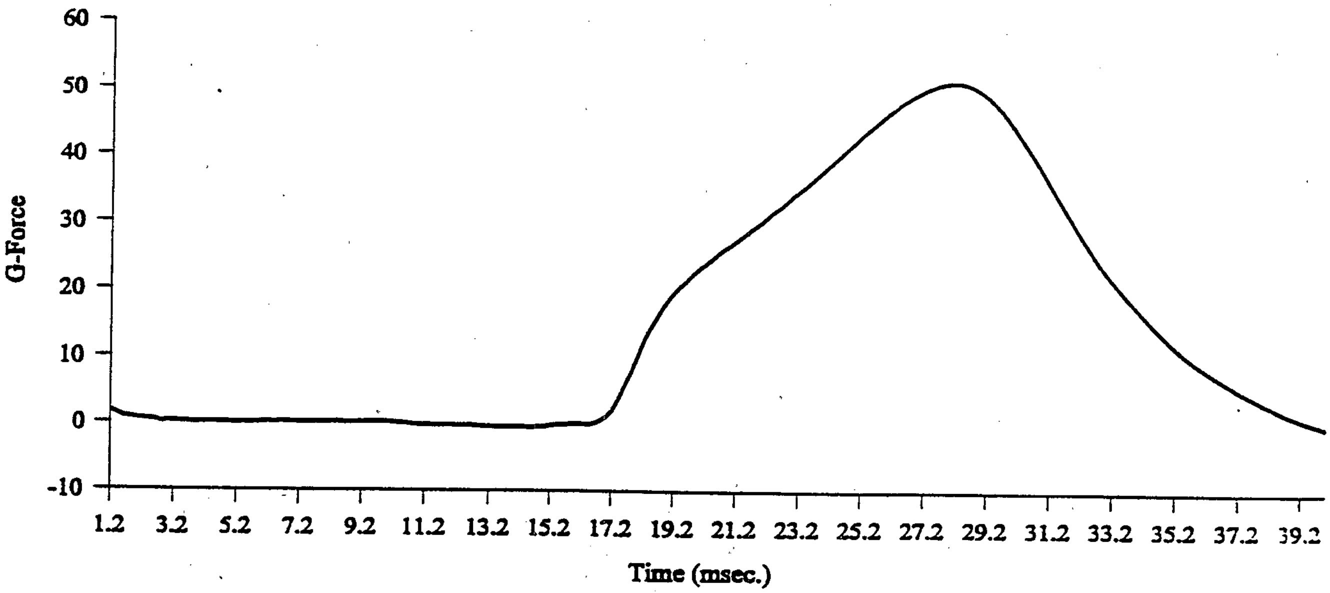


FIGURE 11 - TYPICAL RESPONSE OF RECYCLED PE FOAM TO SINGLE-EVENT IMPACT SHOCK

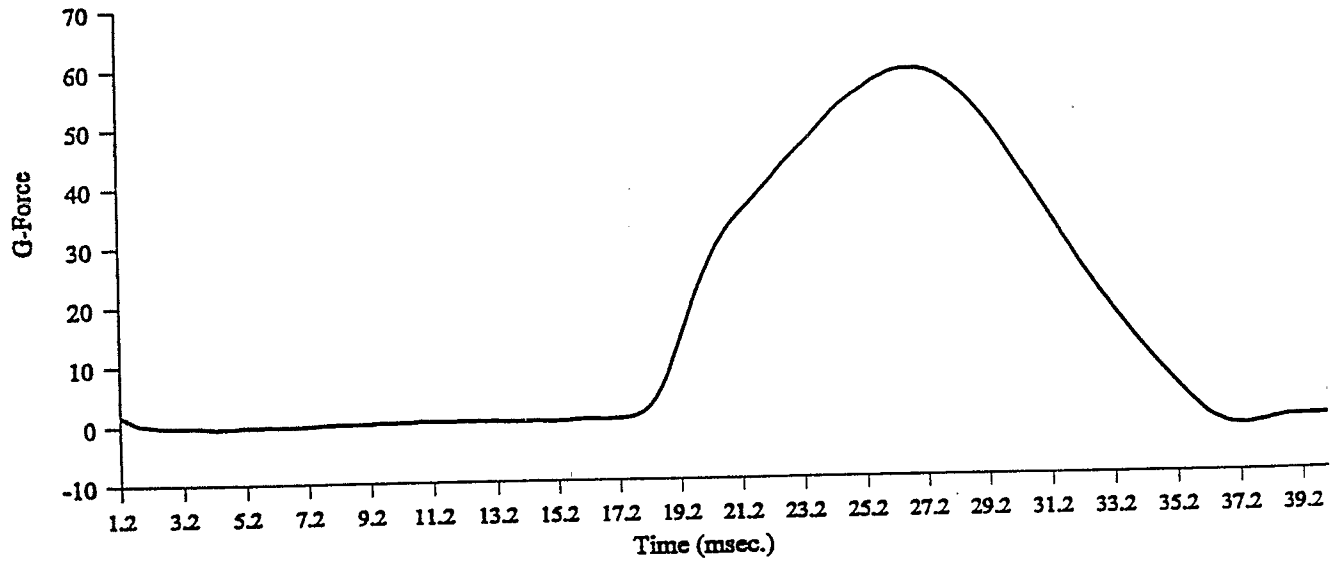


FIGURE 12- TYPICAL RESPONSE OF STARCH-BASED FOAM PLANKS TO SINGLE-EVENT IMPACT SHOCK

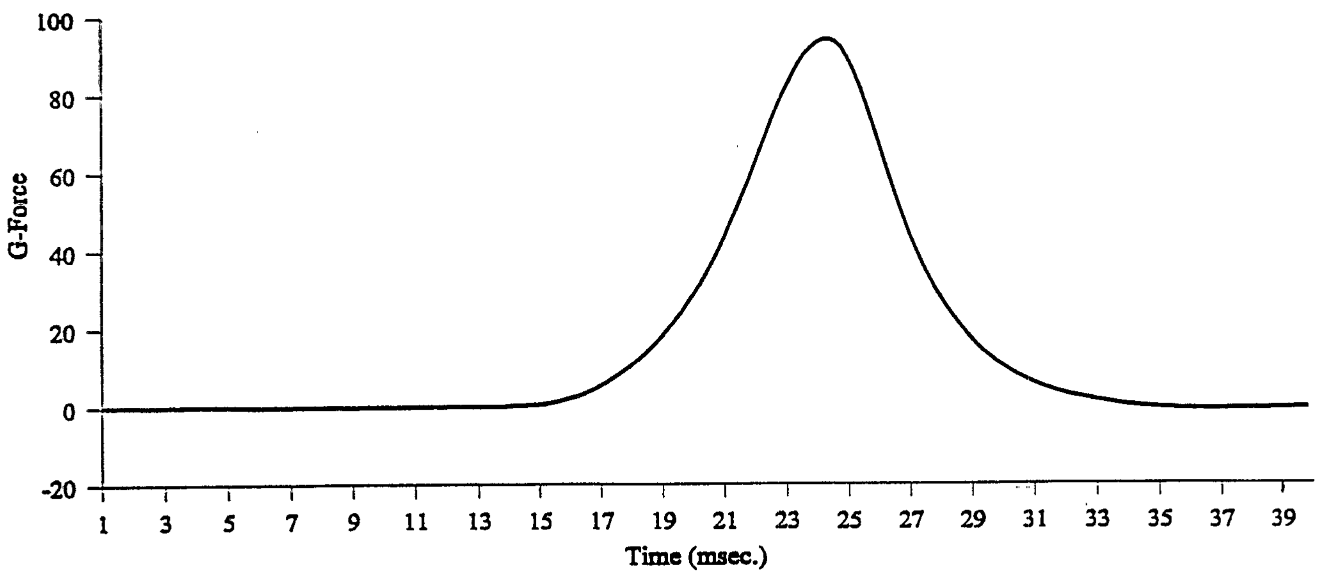


FIGURE 13 - TYPICAL RESPONSE OF LAYERED CORRUGATED PADS TO SINGLE-EVENT SHOCK

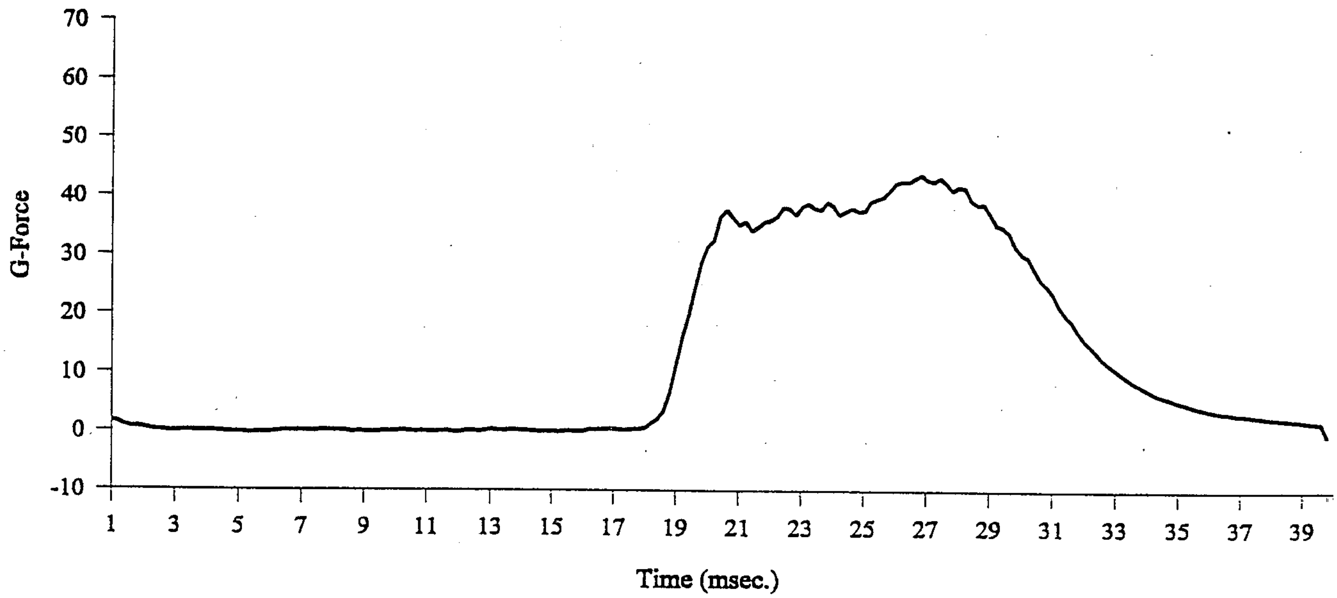


FIGURE 14 - DYNAMIC CUSHIONING CURVE FOR EPS

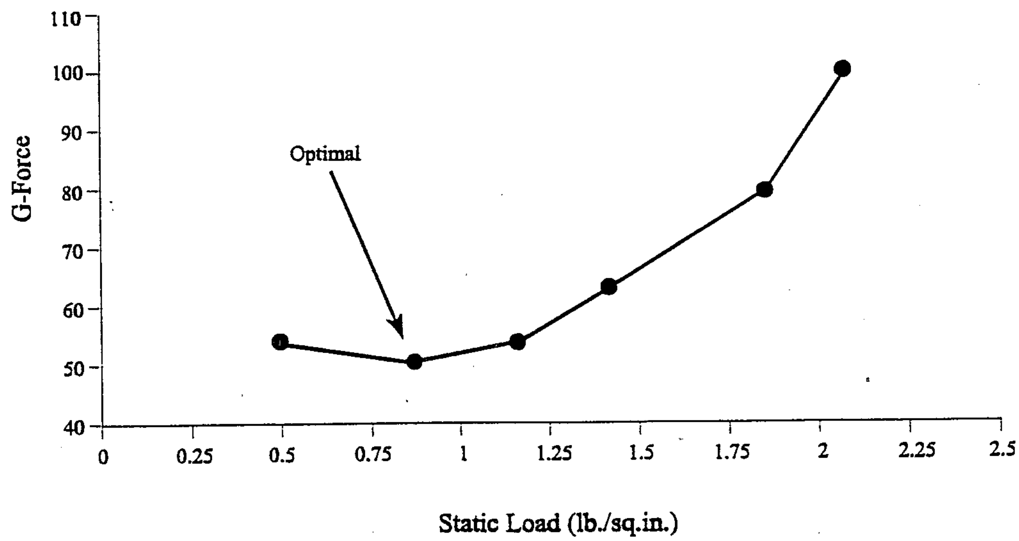


FIGURE 15 - COMPARISON OF DYNAMIC CUSHIONING CURVES FOR RECYCLED PE FOAM AND EPS

Drop Height = 30 inches; Sample Thickness = 1.5 inches

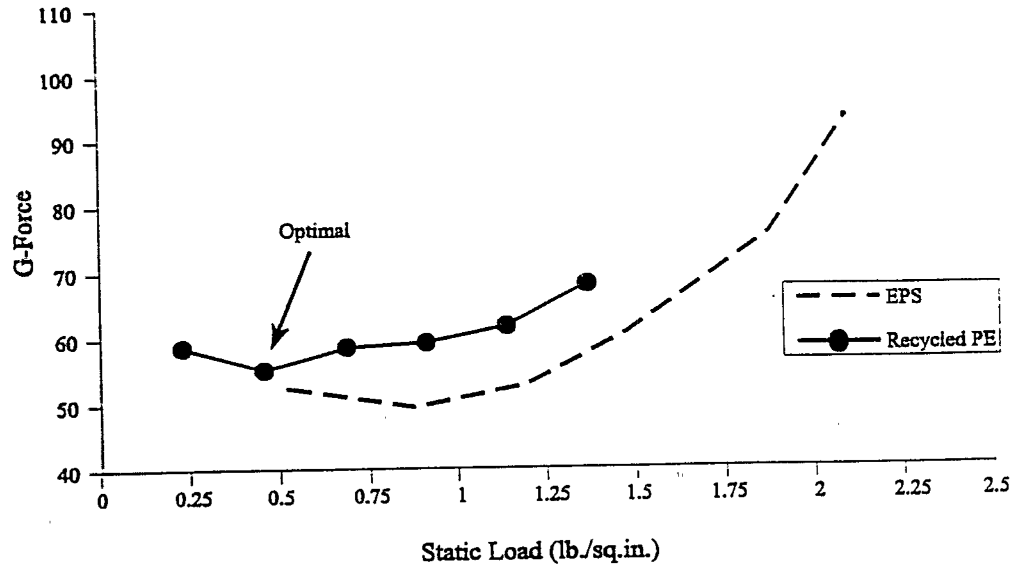


FIGURE 16 - COMPARISON OF DYNAMIC CUSHIONING CURVES FOR STARCH-BASED FOAM AND EPS

Drop Height = 30 inches; Sample Thickness = 1.5 inches

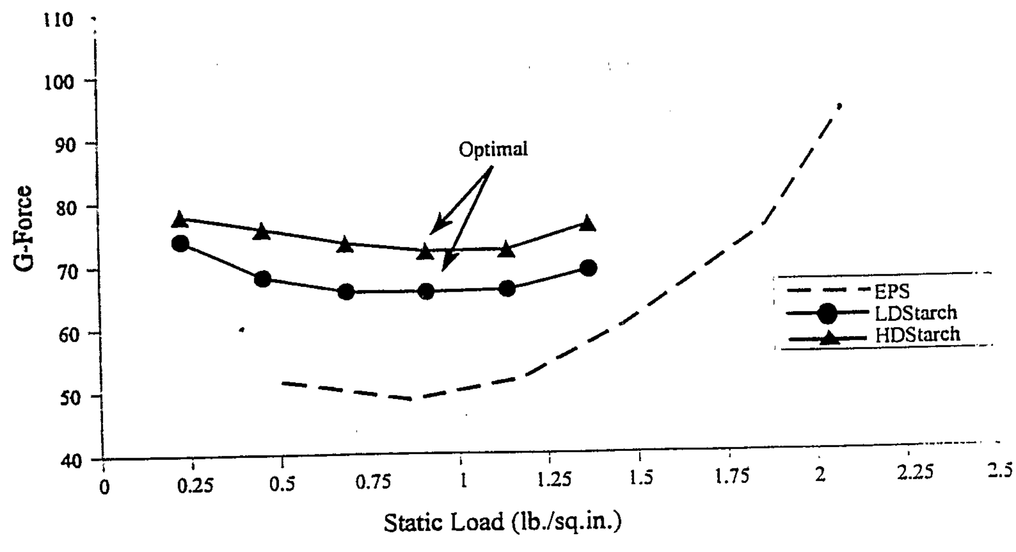


FIGURE 17 - COMPARISON OF DYNAMIC CUSHIONING CURVES FOR LAYERED CORRUGATED PADS AND EPS

Drop Height = 30 inches; Sample Thickness = 1.5 inches

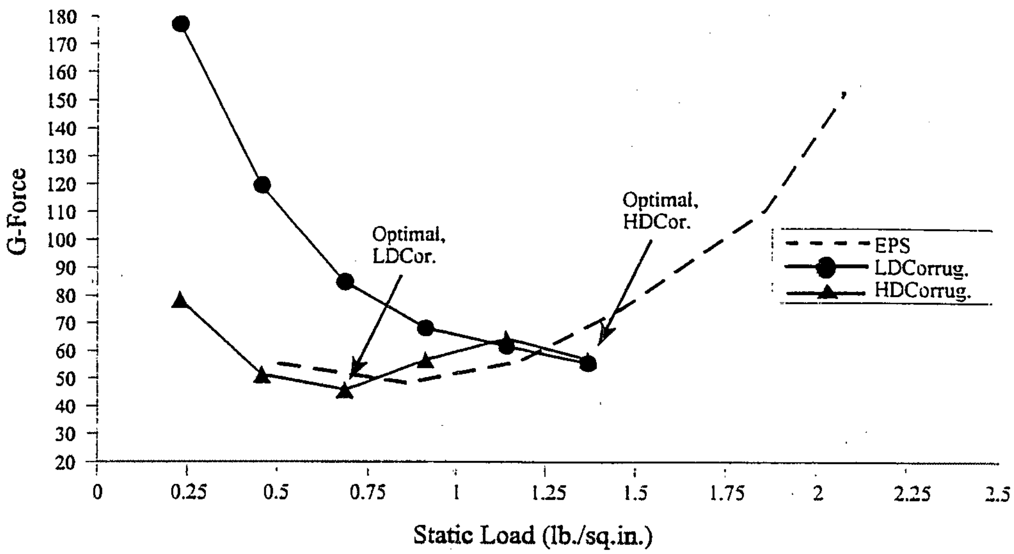


TABLE 3 - SUMMARY OF OPTIMAL STATIC LOADS AND CORRESPONDING G-FORCES FOR EACH MATERIAL		
Material	Optimal Static Load (lb/sq inch)	G-force
EPS	0.82	51
Recycled PE Foam	0.37	55
LD Starch-Based	0.64	66
HD Starch-Based	0.64	72
LD Layered Corrug.	0.52	46
HD Layered Corrug.	0.93	56

Note: Drop Height = 30 inches; Sample Thickness = 1.5 inches

ASTM standard methods specify the measurement and recording of a maximum of 5 consecutive drops on the same sample. Reporting the results of such repeated impact absorption, however, is not required by this method; dynamic cushioning curves typically represent the first drop impact shock response, as Figures 14 through 17 represent. Packaging design engineers and industrial specifications often consider the performance of a material under repeated impacts, however. How a single cushioning material performs under repeated shock impacts will give some indication of how a cushioning system of a package-product system will perform if, for example, it was dropped repeatedly onto its side. Table 4 is included in this discussion of dynamic cushioning to present the decay of each sample's cushioning properties when subjected to a repeated static load. This table presents the experienced G-force under optimal static load conditions for each sample for repeated drops. The percent increase of the experienced G-force for each drop, as compared to the G-force of the first drop, is presented in parentheses.

TABLE 4 - DECAY OF CUSHIONING PROPERTIES FOLLOWING REPEATED SHOCK IMPACTS AT OPTIMAL STATIC LOAD CONDITIONS					
Material	G-force (% Change) Experience During Drop # . . .				
	1	2	3	4	5
EPS	51.2	76.9 (50.2%)	87.3 (70.7%)	92.3 (80.4%)	94.5 (84.7%)
Recycled PE Foam	55.1	59.7 (8.4%)	61.0 (10.6%)	61.8 (12.1%)	61.3 (11.1%)
LD Starch-Based	62.6	83.4 (27.0%)	93.7 (42.8%)	100.5 (53.2%)	106.2 (61.8%)
HD Starch-Based	72.0	81.8 (13.6%)	86.9 (20.7%)	90.4 (25.5%)	93.6 (30.0%)
LD Layered Corrug.	48.9	106.1 (131.2%)	136.8 (198.2%)	ND	ND
HD Layered Corrug.	55.6	86.5 (55.5%)	104.1 (87.2%)	128.3 (130.8%)	152.1 (173.5%)

ND: No Data. Experienced G-force exceeded the limits of the computer system settings; data were truncated and an accurate reading was not recorded.

EPS is used by many consumer product manufacturers for its multiple-impact protective properties. However, from the results of this study, two alternative materials out-perform EPS in this regard. Recycled PE foam represents the most resilient material; it is able to withstand multiple and subsequent shock impacts with as little as 12 percent decay of cushioning properties. This characteristic of PE foam makes it suitable for reusable/returnable packaging applications. The starch-based plank product also out-performs EPS after repeated shock impacts, with a 30 percent and 62 percent decay in cushioning properties for high-density and low-density starch-based planks, respectively. The results of Table 4 also show a possible limitation of layered corrugated products. The low-density corrugated pads lost nearly all their cushioning properties after three subsequent drops, while the high-density material exhibited the greatest degree of decay at Drop #5 of 173.5 percent.

It should be noted that the results of such tests are highly dependent on the time delay between subsequent drops, as well as the true distribution environment through which the package-product system will travel. For the test results presented in Table 4, an average of one minute transpired between subsequent drops (following ASTM methodologies). It has been shown, however, that many materials (particularly plastics) have a recovery time of minutes, hours, and even days. Therefore, the longer a cushioning material has to recover from a single impact, the better it may perform upon subsequent impact. Furthermore, in typical transport environments, it is unlikely that a package would experience such frequent impacts, offering the cushioning material more time to recover.

Extreme Conditions. Two additional test series were performed which evaluated the same cushioning properties under extreme temperature and humidity conditions. Though typically not considered an issue for polymeric materials such as EPS and PE, temperature and humidity can effect the cushioning capabilities of natural materials (i.e., starch and corrugated). Therefore, two standard conditions were selected for evaluation: desert and tropical. Time constraints did not allow for the evaluation of the impacts that freezing conditions have on test samples.

Using the results of the first dynamic drop series, a single static load was considered for each material; this static load was at or near the optimal portion of the dynamic cushioning curve for each material as presented in Table 3. Therefore, the static loads considered for each material were as follows: 0.82 lb/sq inch for EPS; 0.37 lb/sq inch for recycled polyethylene foam; 0.52 lb/sq inch for layered corrugated pads; and 0.64 lb/sq inch for starch-based planks. As before, three replicate samples at these static loads were tested and the peak G-forces for the first drops averaged. A comparison of the average G-forces are presented in Table 5. The percent-change for each recorded average G-force is also presented in parenthesis for Desert and Tropical Conditions as it compares to the G-force under standard conditions. Supporting data are published in a separate report, and can be obtained from the U.S. EPA.

TABLE 5 - COMPARISON OF OPTIMAL Gs UNDER EXTREME CONDITIONS

Material	Static Load (lb/sq inch)	Optimal G-forces Recorded Under . . .		
		'Standard' Cond.	Desert Cond.	Tropical Cond.
EPS	0.82	51.18	53.60 (+4.7%)	49.06 (-4.1%)
Recycled PE	0.37	55.13	59.63 (+8.2%)	58.57 (+6.2%)
Layered Corrugated	0.52	45.89	45.21 (-1.5%)	67.14 (+46.3%)
Starch-Based Planks	0.64	65.62	72.31 (+10.2%)	ND

ND: No Data. Due to sample deformation (e.g., shrinkage, brittleness, and delamination), dynamic drop tests could not be properly performed.

The results of Table 5 show the significant effects temperature and humidity have on a material's cushioning properties. EPS experienced the least significant change of all materials in the recorded G-force for both desert and tropical conditions. The +4.7 percent and -4.1 percent change can be interpreted as insignificant (less than 10 percent of peak G-force) for most packaging applications. The changes in peak G-forces experienced by the recycled PE samples are a bit more significant. Under both extreme conditioning environments the recorded G-force increases, possibly due to the high temperature causing a softening of the polymeric material. However, as with EPS, the +8.2 percent and +6.2 percent changes can be interpreted as insignificant for most packaging applications.

The natural cushioning materials were affected much more significantly by the extreme conditions evaluated in this study. The change in cushioning properties for layered corrugated pads under desert conditions was the least significant for all test materials. This was an unexpected result due to the fact that an essential ingredient of corrugated pads is moisture; at a relative humidity of 15 percent it would be expected that most of this essential moisture would have been lost, causing the pads to become less pliable and therefore resulting in a much greater G-force. This was not the case, and the corrugated pads experienced the least change (1.5 percent) in cushioning properties under these conditions. On the other side of the humidity spectrum, too much moisture may cause the corrugated pads to become soggy, reducing the cushioning potential. This may have been the cause of the results recorded under tropical conditions (46.3 percent increase in G-force, or decrease in cushioning potential). From these results, a designer may want to consider the effects of temperature and humidity, and the conditions under which the package-product system will operate.

Temperature and humidity can play a dominant role in the cushioning properties of starch-based foams due to the chemical and physical properties of the material. Though not formally evaluated during this study, material shrinkage and increased brittleness, two common results of extreme conditions, were both experienced. Qualitatively, under desert conditions the samples experienced minor dimensional changes; sample area decreased while the thickness increased due to delamination of the individual layers. The samples were also observed to be less pliable (i.e., increased brittleness). Under tropical conditions, the change in physical properties was much more significant. Sample thickness could not even be measured in a consistent or reproducible manner due to sample distortion and brittleness. Furthermore, the area of the samples decreased due to shrinkage by over 60 percent. Note that the changes in the physical dimensions of other materials were considerably less (i.e., percent difference near or below +/- one percent).

Though the effects of temperature or humidity were not evaluated further in this study, American Excelsior is currently defining and setting boundary conditions under which their products are expected to perform adequately. Test results completed by American Excelsior's starch supplier (National Starch, a division of Unilever) suggest the upper humidity limit is 82.5 percent. Under this relative humidity, with moderate to high temperatures, material deformation is expected to be minimal. National Starch test results are presented in the supplemental publication to this report, available through the U.S. EPA.

Supplemental Studies. Prior to this research project, a number of studies were completed and published by other research organizations on the cushioning properties of selected materials. In the late 1960's and early 1970's, the Forest Products Laboratory, under the control of the U.S. Department of Agriculture, published the first studies on the potential applications of layered corrugated as a cushioning material. Published under a number of titles [22-29], these test series systematically evaluated different corrugated designs, different pad thicknesses, and different temperature and humidity conditions. These studies expanded the potential application of corrugated paperboard beyond the use of boxes. Further studies completed by the same laboratory evaluated the cushioning offered by the corrugated container itself.[30, 31]

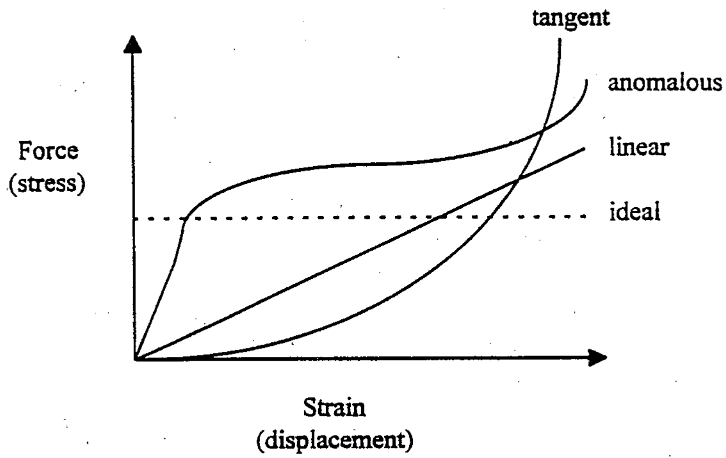
The second prominent and applicable test series addresses the issue of recycled resin content in EPS cushioning pads. A study completed by researchers at Santa Clara University in California presented the effects various recycled resin contents have on the static and creep properties of EPS.[32] Other publications present results on the dynamic cushioning behavior of various recycle resin content EPS samples.[33, 34] Most revealing about these test results was that recycled content had little or no effect on the performance of EPS.

Finally, though not considered in this research project, loose-fill cushioning materials have also been the subject of many other previously completed projects. The most complete and in-depth study on loose-fill cushioning characteristics was conducted by Michigan State University. One publication of their results is "Comparison of Various Loose Fill Cushioning Materials Based on Protective and Environmental Performance."[35]

STRESS-STRAIN TESTS

The ratio of stress to strain is a characteristic constant of a material. The measure of a material's stress-strain relationship is independent of sample thickness and can be used as a design parameter for cushioning applications. Stress is defined as the force per unit area producing deformation in a body. Strain is defined as the deformation resulting from a stress and is typically measured by the ratio of the change to the total value of the dimension in which the change occurred (e.g., percent change of sample thickness). Figure 18 represents the variety of stress-strain curves which are possible when studying the static characteristics of cushioning materials. The figure plots the force applied (i.e., stress) and resulting displacement (i.e., strain) on the y- and x- axes, respectively. An ideal material experiences a constant strain over a wide range of stresses, as presented by the dashed line in Figure 18.

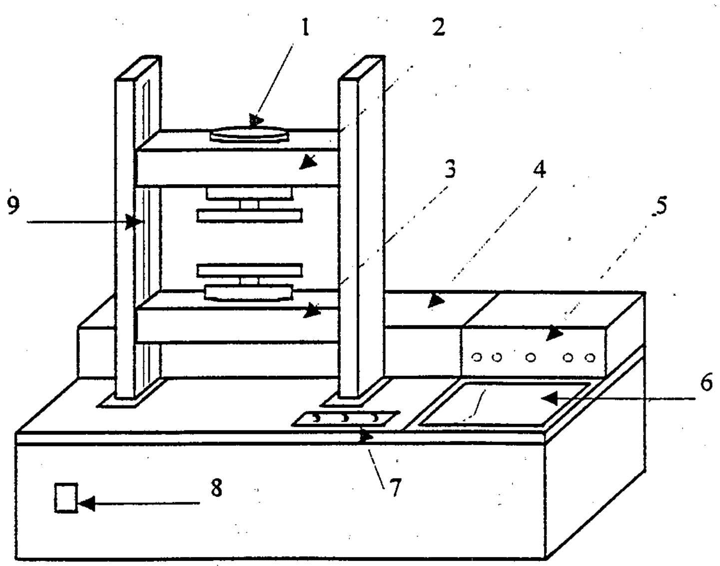
FIGURE 18 - POSSIBLE STATIC STRESS-STRAIN CURVES



Apparatus

The apparatus used to evaluate the stress-strain properties of each material was an Instron 1130. This instrument, schematically represented in Figure 19, consists of four primary components: a load cell, two cross heads, and a strip chart recorder. Capable of analyzing both tensile and compressive properties of materials, the Instron 1130 was mounted with a compression load cell for these experimental runs.

FIGURE 19 - SCHEMATIC DIAGRAM OF STRESS-STRAIN TEST APPARATUS



1 load cell
2 reinforced top crosshead
3 moving crosshead
4 change-gear for chart and crosshead
5 load cell amplifier
6 strip chart recorder
7 crosshead control panel
8 main power switch
9 drive screw

The crossheads of the Instron act as the surfaces between which the material samples are compressed. The upper, reinforced crosshead contains the load cell, and remains stationary throughout the test. The bottom crosshead is moved via a drive screw, thus raising the material sample to the top crosshead. The speed of the drive screw can be set by the user and is controlled by the crosshead control panel and the gears of the gearbox located in the back side of the unit. A material sample, placed on the lower crosshead, is raised until its upper surface is just below the load cell of the upper crosshead. At this time the strip recorder is initiated, the movement of the lower crosshead continued, and the raw stress-strain data recorded. The features of the recorded data can be controlled manually by the load cell amplifier and chart control panel.

Procedure

Though standard stress-strain test methods exist for a variety of materials (e.g., food products and building materials), there is not a standard method that directly applies to cushioning materials or the goals of this research. Therefore, test procedures were adopted from the Instron manual and the ASTM methodology C 365-57, Standard Test Methods for Flatwise Compressive Strength of Sandwich Cores. A step-by-step description of the test procedure followed is included in Appendix B.

Three replicate samples were tested under identical test conditions for four different materials: EPS recycled PE foam, low-density starch-based plank, and low-density layered corrugated pads.[3] The average of each replicate set represents the stress-strain curves presented below. Significant differences within replicate sets were not experienced; standard deviations were well within the tenth percentile as specified in the Quality Assurance Project Plan. Sample conditioning and test conditions were typical of an office environment: 22 °C and 51 percent relative humidity. After setting and recording the desired chart speed and compression rate, a material sample was placed between the two compression blocks. As the moving crosshead raised and began to compress the sample, the graphical chart recorded the stress and strain measurements of the compressometer. These data were then digitized to develop stress-strain data files.

Static Stress-Strain Results

When considering stress-strain relationships, an ideal material exists only in theory. As presented in Figure 18, real materials can exhibit a variety of characteristics. Anomalous materials exhibit ideal characteristics within a section of the stress-strain relationship, while tangent and linear materials exhibit few ideal characteristics. Figure 20 presents resultant stress-strain curves for each of the four materials tested. From this single plot, two distinct curve shapes can be identified. These results reveal both anomalous and linear characteristics within the materials tested.

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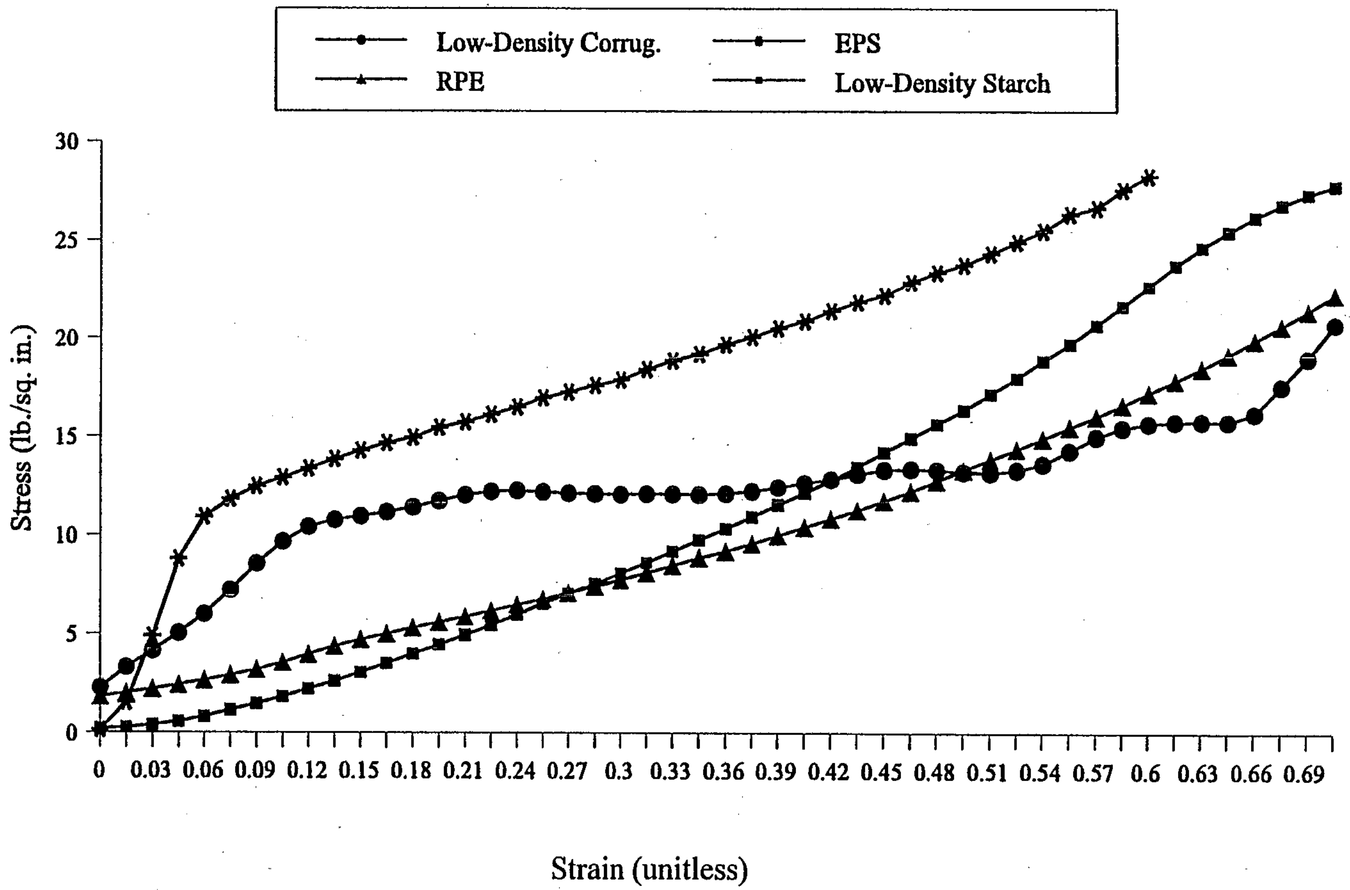
[3] Samples of high-density starch-based plank and layered corrugated pads were not available during these test series. The manufacturers of these materials made high-density samples available to the researchers after stress-strain tests were completed.

FIGURE 20 - COMPARISON OF STATIC STRESS-STRAIN CURVES



The stress-strain curves for the starch-based and recycle PE samples are more linear throughout the strain range tested, while the stress-strain curves for the EPS and layered corrugated samples exhibit a 'shoulder,' or yield point, distinguishing two different sections of the curve (i.e., anomalous materials). The results of the starch-based and PE materials are least desirable since sample deformation occurs throughout the range of stress. Two distinct differences, however, can be made when comparing the various slopes of each stress-strain curve for EPS and layered corrugated.

1. As presented in Figure 18, an ideal material exhibits a constant stress for a wide range of strains. Compare the slope of each curve prior to the shoulder. The slope for the EPS samples is much steeper, while that of the layered corrugated material is flatter. EPS therefore attains a near-ideal profile more quickly, when compared to layered corrugated; this is a desirable quality of a cushioning material.
2. Next, compare the slopes of each curve after the shoulder. The slope after the shoulder for layered corrugated is much less (i.e., approaches horizontal) and therefore is considered more ideal. From the results of this study, low density layered corrugated pads exhibit the most constant stress level over the widest strain range. This is a desirable quality of a cushioning materials.

When the project was initiated, and the technical laboratory test series selected, it was hoped that a relationship could be established between static, stress-strain and dynamic shock cushioning results. This relationship would establish the foundation for a packaging design model, or at least design rules-of-thumb for each of the materials. The relationship was to be established by converting the stress-strain data into stress-force relationships, identical to that of the G-force versus static load relationships of dynamic cushioning curves. Following the completion of the static stress-strain tests, data manipulation revealed that the stress-strain results are rate dependant, or that the resulting strain on the packaging material is a function of the applied stress *and* the rate at which it was applied. As a result, a relationship between the dynamic and static tests could not be established.

Static, stress-strain test results can indicate the amount of set (i.e., compression or settling) a cushioning system will encounter when burdened with a product. This amount of compression must be accounted for when designing a package-product system. Minimal set should occur for those materials exhibiting a shoulder or yield point (e.g., EPS and layered corrugated pads) for stress-strain relationships below this yield point. Linear materials would exhibit some degree of set at any stress-strain relationship. The use of static, stress-strain curves to solve shock cushioning problems is discouraged.[36] Therefore, an evaluation of stress-strain results beyond that of the theoretical discussion presented above, and the qualitative set parameter just mentioned, would not offer additional information of use to this study and the results of the project.

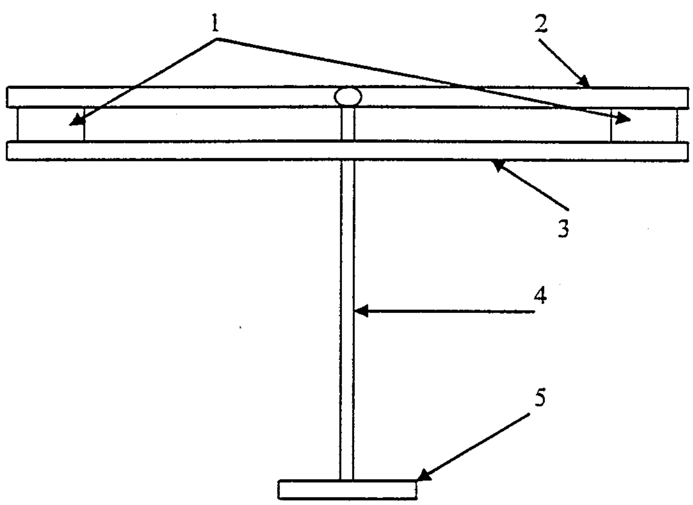
CREEP TESTS

Creep is defined as the amount of set, or compression, a packaging material exhibits when subjected to a continuous load. Creep can occur in all packaging applications, but is most prevalent during storage and transport when the protective packaging is under continuous load from the product, possibly at elevated temperatures. During transport, the agitation resulting from vehicle movement can add to the existing stresses. As discussed above, stress-strain relationships can offer a qualitative measure of material set and creep. To extend this qualitative assessment, rudimentary creep tests were completed for this study.

Apparatus

The apparatus used for evaluating creep is schematically presented in Figure 21. The apparatus consists of a secured bottom moment-arm plate, free moving top moment-arm plate, 24-inch beam at the bottom of which is mounted a weight plate. Two different packaging material samples are placed between the top and bottom moment-arm plates. Weighted with the appropriate load, the apparatus is placed in a temperature controlled oven for the duration of the study. Two identical apparatus were used in a common oven.

FIGURE 21 - SCHEMATIC DIAGRAM OF CREEP TEST APPARATUS



1 material samples
2 free-moving, top moment-arm plate
3 secured, bottom moment-arm plate
4 weight-bearing beam
5 weight-bearing platform

Procedure

The creep test involves applying a load to each of the four samples for a ten-week period in a temperature controlled oven at approximately 40 °C. Once in the oven, changes in specimen thickness were recorded after one, two, five, ten, 15, and 20 minutes. Measurements were then reported at one, two, five, ten, and 15 hours, followed by one, two, five, and seven days. For the duration of the experiment, measurements of sample thickness were recorded once per week.

Utilizing the results from the stress-strain tests, stress levels were determined for each material sample (i.e., 5 percent of strain). The following loads were required for each of the samples in order to operate at the desired 5-percent strain, assuming a 4 x 4 inch square sample; EPS, 140 lb; starch-based foam plank, 5 lb; layered corrugated pads, 68 lb; and recycled PE foam, 35 lb. Due to the large variance in these loads, and the fact that two different samples were being tested together, sample sizes and moment arms (distance between beam and weights and samples) were adjusted. A 4 x 4 inch starch-based foam plank sample was paired with a 3 x 3 inch recycled

PE foam sample with an applied load of 22 lb. The location of the beam was adjusted resulting in moment arms that distributed a 3 lb load to the starch sample and a 19 lb load to the PE sample. Similarly, a 3 x 4 inch layered corrugated pad sample was paired with a 4 x 4 inch EPS sample. The beam and accompanying weight was adjusted to apply an 85 lb load to the EPS sample and a 38 lb load to the corrugated sample.

Creep Test Results

The results of these tests revealed that creep is an issue for all materials. The most significant creep was exhibited by the polymeric materials (EPS and recycled PE foam), while the layered corrugated pads exhibited the least amount of creep. This creep test apparatus and procedure was not intended to represent a definitive measure of creep for any of the materials. This experiment was conducted, and the qualitative results presented in this study for completeness. For a greater degree of certainty and measure of creep, additional tests are required.

PROTOTYPE DEMONSTRATION

As stated in Chapter 3, four key considerations must be addressed when designing a cushioning system: fragility level; distribution environment; impact shock; and cushioning configuration. The technical results presented above represent the general or generic cushioning properties and capabilities of each material, i.e., the impact shock considerations under specific distribution environments. A packaging designer must combine this information with a fragility level and knowledge of the expected distribution environment to develop an effective and economical cushioning configuration. How the designer accomplishes this is discussed below.

Cushioning Design

A packaging designer can combine the knowledge of a product's fragility level and weight with the information supplied by a dynamic cushioning curve to establish guidelines within which an effective cushioning configuration must be developed. Figure 22 presents how this information is combined to develop cushioning packaging. Using the calculated bearing area as a guideline, a package designer can optimize both pad thickness and material use by engineering the configuration of the cushion. For example, the use of fins in the cushioning configuration can reduce the quantity of material used while maintaining pad thickness and required bearing area.

The use of fins and other shapes within the configuration of a cushioning system is limited to some extent by the material(s) used. The processes used to mold EPS pads is very amenable to a variety of complex shapes, while starch-based planks, recycled PE foam, and layered corrugated pads require die cutting and separate assembly of parts if fins and other complex designs are used. This ability or inability to manufacture specific cushioning configurations is a critical issue affecting the choice of a cushioning material and is addressed in Chapter 6, Economic Evaluation.

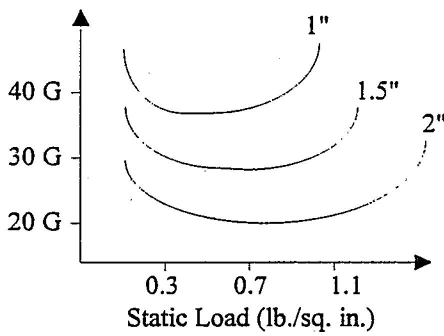
FIGURE 22 - THEORETICAL DESIGN OF CUSHIONING PADS - A FOUR STEP PROCESS

A

Product Information

Fragility Level = 30 G
Weight = 8 lb.

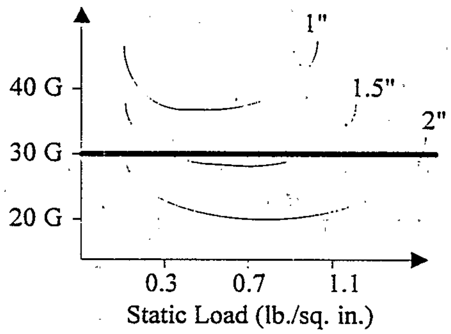
Cushioning Material Information



Dynamic cushioning curves for Material X at a drop height of 30 inches and varying material thicknesses.

B

With this information, draw a horizontal line from the fragility level across the plot of dynamic cushioning curves.



Dynamic cushioning curves with optimal regions below this line represent materials with thicknesses which offer adequate cushioning for that particular product; optimal regions above this line do not offer sufficient cushioning.

C

To minimize material consumption, design guidelines should be calculated based on the dynamic results of the 1.5-inch thick material. Therefore, the optimal static load to design towards will be approximately 0.7 lb./sq. in.

To function within this region of the cushioning curve, the weight of the product must be distributed over a sufficient area (i.e., bearing area) of cushioning material. Static load is defined as a known weight distributed over a specified area. Therefore:

static load = weight/area

or

bearing area = weight/static load
= 8 lb./(0.7 lb./sq. in.)
= 11.43 sq. in.

D

The packaging designer uses this as the guideline to develop an effective cushioning configuration. The calculated bearing area must be designed for each side and corner of the package-product system.

Corner pads, end caps, and planks represent simple cushioning geometries which offer sufficient bearing area on all sides to protect the product. Convolutions, fins, and other engineering shapes maintain material thickness and bearing area while minimizing material consumption.

The center of gravity must also be considered when designing cushioning systems. More bearing area of the cushioning system should be placed under the center of gravity to absorb the resulting load in that region.

Once a cushioning configuration has been developed, however, the package designer cannot fully predict how a cushioning system will behave and perform in an actual package-product application. Therefore, prototype demonstrations must be conducted to evaluate the performance of designed package-product systems in specific applications. A method to evaluate the performance of a package-product system has been established by the International Safe Transit Association (ISTA, formerly the National Safe Transit Association) in the Pre-Shipment Test Procedures.

This methodology, summarized in Figure 23, has been modified by many manufacturers to address specific requirements of their products and distribution systems. An example of such a modification would be to increase the drop height a package-product system must withstand based on the product's weight, thus increasing the protective demands of the cushioning system. The standard vibration and drop test sequences of the ISTA Pre-Shipment Test Procedures were used during prototype demonstrations for this study.

FIGURE 23 - ISTA TEST PROCEDURES FOR PACKAGE-PRODUCT SYSTEMS WEIGHING UNDER 100 POUNDS

Drop Test	
Step 1	Identify and label the following surfaces of the package-product system: top as '1'; right side as '2'; bottom as '3'; left side as '4'; front as '5'; and back as '6'.
2	Identify edges by the number of those two surfaces forming that edge. For example, the edge forming the top and right side is identified as 1-2.
3	Identify corners by the numbers of those three surfaces which meet to form that corner. For example, the corner formed by the right side, bottom, and front is identified as 2-3-5.
4	The drop height shall be as follows based on package-product system weight: 1 through 20.99 lb, 30 inches; 21 through 40.99 lb, 24 inches; 41 through 60.99 lb, 18 inches; and 61 lb up to and including 100.00 lb, 12 inches. (specifications do exist for heavier products)
5	Drop or impact the package-product system as specified under Step 4 in the following sequence: 1) the 2-3-5 corner; 2) the shortest edge radiating from that corner; 3) the next longest edge radiating from that corner; 4) the longest edge radiating from that corner; 5) flat on one of the smallest faces; 6) flat on the opposite small face; 7) flat on one of the medium faces; 8) flat on the opposite medium face; 9) flat on one of the largest faces; and 10) flat on the opposite largest face.
6	Inspect both the package and the product. The package-product system shall be considered to have satisfactorily passed the test if, upon examination, the product is free from damage and the container still affords reasonable protection of the contents.
Vibration Test	
Step 1	Place package-product system on vibration table in the position in which it is normally shipped.
2	Set the vibration frequency at the minimum speed sufficient to cause the package-product system to leave the table momentarily so that a shim may be inserted at least 4 inches between the bottom of the package-product system and the surface of the table.
3	Vibrate the package-product system for a total of 14,200 vibratory impacts.
4	Inspect the exterior of the container for visible damage. Check for looseness of product or components. When practical, inspect the product and then reclose the container.

Source: International Safe Transit Association. "Pre-Shipment Test Procedures - Procedure for Testing Packaged-Products, Weighing Under 100 Pounds." Revised April 1988.

Prototype Demonstration Results

Each material vendor was asked to identify potential industry partners from their current and potential clientele which would demonstrate the application of an alternative material. Each material vendor also had the opportunity to design a packaging system for a VCR currently marketed by Philips and packaged in EPS end caps. Five separate prototype demonstrations were completed within the context of this study:

- Two EcoPlank prototype designs for Philips' VCR.
- One layered corrugated prototype design for Philips' VCR.
- Two EcoPlank prototype designs for a MAYTAG range-top glass component.

The cooperation of a vendor of recycled PE was not obtained in this study; prototype packaging for performance testing was therefore not obtained.

To establish a baseline for evaluating performance results, performance testing was first conducted on a VCR packaged in the EPS end caps currently used by Philips. These results are presented below, followed by a description of each alternative material prototype design and the results of the ISTA Package-Product System Tests.

Performance of EPS in a VCR Application. As previously stated, VCRs marketed by Philips are currently packaged with EPS end caps. Two restrictions are placed on any alternative packaging design if it were to replace this application of EPS:

1. The prototype cushion-product system must fit into the existing corrugated box to maintain shipping standards.
2. Following drop tests, the VCR must function properly as determined by Philips' quality control department.

Philips has sized each package-product system to optimally utilize available cargo capacity within various modes of transportation; this is known as "cube efficiency." Therefore, the first restriction is placed on alternative designs to maintain this cube efficiency. Chapter 6, Economic Evaluation, discusses this issue and other economic considerations in more detail.

Though other products manufactured and marketed by Philips require a minimum level of protection (i.e., a fragility level for the product is specified), such specifications are not placed on the VCR and the package-product system. As a result, the second restriction above represents the criterion used to evaluate the performance of a packaging design for the VCR. However, this qualitative measure of the performance of a package-product system does not allow for a comparative evaluation between designs. Therefore, to quantitatively measure the performance of EPS and other packaging designs, a transducer was mounted to the plastic casing of the VCR and acceleration-time histories were recorded during the standard sequence of drop tests.

Further alterations were made to Philips' testing methods. Philips typically subjects its package-product systems to drop heights greater than those specified by ISTA (as presented in Figure 23). To offer performance results based on the internationally accepted ISTA standards, however, the VCR package-product system was subjected to a drop height of 30 inches (the VCR weighs less than 20 lb), rather than Philips' required drop height. The influence of vibration tests on the effectiveness of a package design is considered minimal by Philips due to the light weight of the VCR. Vibration tests were therefore omitted from the evaluation of alternative packaging designs in this application.

Table 6 summarizes the maximum G-forces experienced by the VCR during the drop test sequence; the measured G-force for each of the six flat surfaces of the package-product system is presented. The maximum G-force experienced by the product was 142 on the top surface of the package-product system. This force, as were all the recorded forces, was greater than expected by the packaging design engineers at Philips. The functionality of the VCR was not compromised, however, and the design is therefore acceptable. The values in Table 6 are used to quantitatively compare the performance of each prototype design to that of the EPS end caps.

Data resulting from the corner and edge drops are not presented in Table 6 due to their irrelevance to the overall evaluation. The transducer was mounted to the front or back of the VCR. As a result, corner and edge drops do not have a dominant axis of motion; energy is displaced across two or more axes, and therefore does not result in maximum resultant force or offer relevant information to the overall performance of the package design.

TABLE 6 - QUANTITATIVE PERFORMANCE ASSESSMENT OF EPS END CAPS

Impact Surface	Maximum G-Force
Left Side	89
Right Side	112
Front	73
Back	100
Bottom	110
Top	142

<u>First EcoPlank Prototype for the VCR</u>. American Excelsior was asked to design a cushioning system for Philips' VCR currently packaged in EPS end caps. Following the restrictions placed on the design by Philips, the first of two cushioning systems designed by American Excelsior can best be described as edge pads. Two L-shaped pads protect the left and right bottom edges of the product by running from the front of the box to the back; the VCR is centered on these pads and two additional L-shape pads protect the front and back edges of the product by running from left to right.

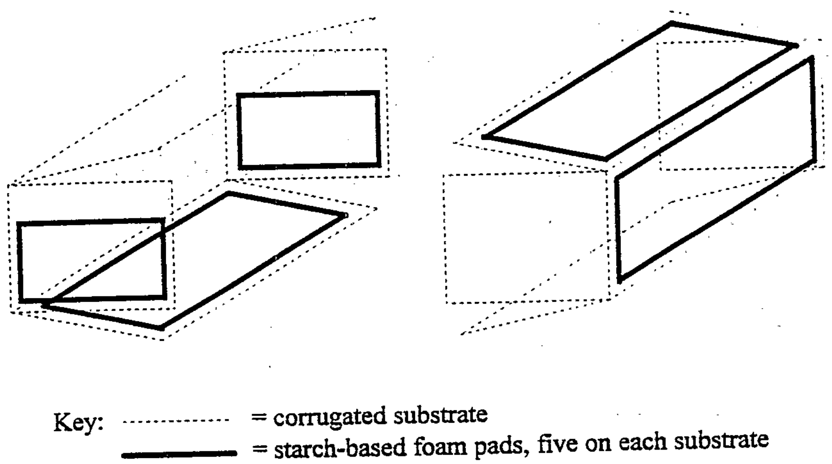
Dynamic drop tests were run on this starch-based prototype package-product system. The package-product system was dropped from a height of 30 inches on the ten surfaces identified in Figure 23. Minimal deterioration of the cushioning system was identified following this test series; each L-shaped pad was still fully intact. Inspection of the VCR case showed no appreciable damage either. Inspection of the VCR by QC personnel, however, revealed internal damage to the working electronics of the unit. Running through a series of QC checks, each function of the VCR operated as designed (fast forward, rewind, play, pause, etc.) until the record function was tested. When recording on a used cassette, a visual image could be recorded, but the sound was not. In fact, the sound corresponding to the last image taped on the cassette still remained. Therefore, the electronics which erase and record sound were damaged. Though considered a minor failure, this first prototype packaging design did not pass the required test procedures.

Unfortunately, acceleration-time histories during drop tests were not accurately recordedby the computer data acquisition system; transducer readings were inadvertently truncated by the computer system and the actual maximum G-forces for each flat-surface drop could not be determined. Based on estimates, however, a maximum G-force of nearly 200 was recorded when the package-product system was dropped onto its top surface. This value exceeds the maximum G-force experienced during package-product system drops which employed EPS, and thus may have caused the functional failure of the VCR.

The package-product system was therefore evaluated to identify possible improvements. The primary area of improvement identified was in terms of bearing area. The bearing area offered by the prototype design was too large considering the weight of the VCR and the results of dynamic drop tests during this study. Based on these observations, and the continued interest of Philips and American Excelsior in this evaluation, a second prototype design was developed. This new prototype design optimized bearing area and material usage.

<u>Second Starch-based Prototype for the VCR</u>. The second cushioning system designed by American Excelsior combined EcoPlank pads and a corrugated substrate into a design schematically represented in Figure 24. Five separate EcoPlank pads were glued to a single sheet of corrugated which served to position the pads in the proper locations around the VCR. Two such EcoPlank/corrugated pads composed a functional unit, one pad for each side of the VCR. Figure 24 shows the two separate corrugated substrates (dashed lines) and the position of only five of the ten total Eco-Plank pads; each substrate surface has an EcoPlank pad attached to it.

FIGURE 24 - SCHEMATIC OF SECOND ECOPLANK PROTOTYPE DESIGN FOR VCR



Dynamic drop tests were run on this starch-based prototype package-product system. The package-product system was dropped from a height of 30 inches on the ten surfaces identified in Figure 23. Again, minimal deterioration of the cushioning system was identified following this test series. Inspection of the VCR case showed no appreciable damage either. Inspection of the VCR by QC personnel revealed no damage to all functions of the VCR. Internal inspection of circuit boards and other electronics did not reveal any damage either.

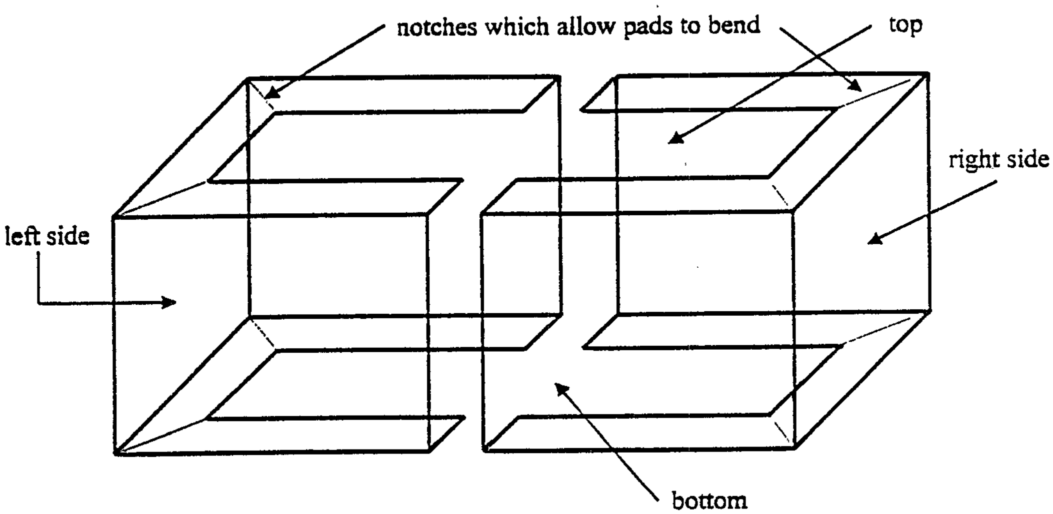
Quantitatively, the G-forces recorded for this application of EcoPlank were comparable to those recorded for the application of EPS cushioning. These figures are presented in Table 7. Though the G-force experienced by the VCR on the top drop exceeded that of the EPS design, the functionality of the product was not sacrificed and the design passed the imposed requirements. The prototype design, therefore, satisfied all relevant tests and restrictions placed on it by Philips.

TABLE 7 - QUANTITATIVE PERFORMANCE ASSESSMENT OF ECOPLANK PROTOTYPE DESIGN

Impact Surface	Maximum G-Force
Left Side	73
Right Side	70
Front	76
Back	54
Bottom	99
Top	152

Layered Corrugated Prototype for the VCR. Menasha Sus-Rap was also asked to design a prototype package for the VCR. Encouraged by the performance of layered corrugated pads in the dynamic tests (i.e., lower optimal G-force than EPS), an effective prototype design for the VCR was considered possible. Conforming to the restrictions established by Philips, and applying similar design features used in many furniture applications, Menasha designed a cushioning system consisting of two U-shaped channel pads that surround each end of the VCR. Each channel pad is notched to allow the pad to bend around the VCR corners. Flat pads are sparingly used to fill the void space between the channel pads and the corrugated box. The channel design is schematically represented in Figure 25.

FIGURE 25 - SCHEMATIC OF LAYERED CORRUGATED PROTOTYPE DESIGN FOR VCR



This prototype package-product system was dropped from a height of 30 inches on the ten surfaces identified in Figure 23. Though the cushioning system noticeably deteriorated as a result of this drop series, an inspection of the VCR showed no appreciable external damage. Inspection of the VCR by QC personnel revealed no damage to all functions of the VCR. Internal inspection of circuit boards and other electronics did not reveal any damage either. The prototype design, therefore, satisfied all relevant tests and restrictions placed on it by Philips. Quantitatively, the G-forces recorded for the application of layered corrugated pads were comparable to those recorded for the application of EPS cushioning. These figures are presented in Table 8.

TABLE 8 - QUANTITATIVE PERFORMANCE ASSESSMENT OF FIRST LAYERED CORRUGATED PROTOTYPE DESIGN

Impact Surface	Maximum G-Force
Left Side	73
Right Side	62
Front	112
Back	105
Bottom	ND
Top	98

ND: No Data. Acceleration-time data were truncated by computer system resulting in an unknown peak.

Though the bearing area of the prototype design was not optimal (as much as 5.5 times greater than theoretically required based on this study's dynamic test results) the cushion system functioned adequately. Optimization of this design would include reducing the bearing area. This change would reduce the amount of material used, thus reducing cost and potentially improving the performance of the packaging. Due to time restrictions, the optimization of this design was not possible within the contexts of this project.

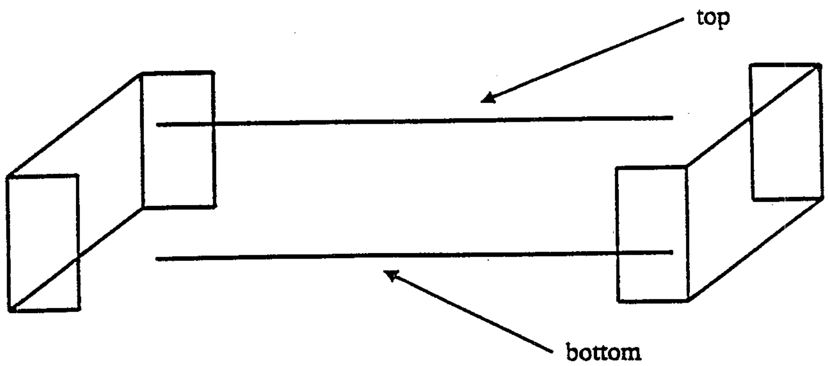
<u>First EcoPlank Prototype for MAYTAG's Glass Component</u>. MAYTAG operates a distribution facility in Milan, Tennessee which supports (i.e., supplies parts to) the customer service needs of MAYTAG, Admiral, JENN-AIR, and Magic Chef across the country. Receiving most of the parts and materials in bulk from the manufacturers, the distribution facility is responsible for individually packaging single-unit orders requested by service representatives. Protective packaging of fragile parts is accomplished using a variety of packaging materials including polyethylene foam plank, EcoFoam loose fill, plastic bubble pack, and crinkled-up newsprint.

Ineffective packaging of tempered glass panels is a current problem at MAYTAG. These tempered glass panels are replacement parts for kitchen ranges (tops, control panels, etc.), and come in a variety of shapes and sizes. Bubble pack or corrugated pads are currently the typical materials selected to package these parts for distribution. The rate at which these parts are damaged during shipment, however, is quite high. The cost of this damage is one of the highest within this facility for a particular product line. As a result, MAYTAG was interested in testing a variety of design options, and agreed to test EcoPlank on one line of glass panel - a long, narrow control panel. Beyond effectiveness and cost, there were no restrictions placed on American Excelsior for this prototype design.

Due to the current rate of failure experienced by MAYTAG, American Excelsior approached this situation from the side of over design; once a passing design was proven effective, optimization of material use and package size could follow. The first prototype design for the control panel utilized a great deal of EcoPlank to protect the top and bottom of the glass. The glass panel itself was nestled in a die-cut sheet of foam sandwiched between the top and bottom pads. Though the test results of this initial design were positive, improvements were possible that would minimize package-product size and material usage. The optimal design and further test results are presented below.

Second EcoPlank Prototype for MAYTAG's Glass Component. Center staff met with MAYTAG and American Excelsior representatives to discuss the initial design and test results, and to identify design features which could be optimized. From this discussion, three significant changes were suggested and implemented. The changes better utilized the cushioning strengths of EcoPlank, and reduced pad volume by nearly 75 percent. The final design consists of two end caps which support the glass panel on all sides, and two pads that run along the top and bottom of the panel to absorb vibrations. Figure 26 schematically represents this new design.

FIGURE 26 - SCHEMATIC OF FINAL ECOPLANK PROTOTYPE FOR MAYTAG'S GLASS PANEL



The results of this optimized design were positive. The optimized prototype package-product system was first subjected to vibration tests at 220 cycles per minute for one hour. Following vibration tests there was no observed degradation of the cushioning material, and the glass panel remained tight within the package. The package was then subjected to the standard series of ten drops (i.e., dynamic impact tested) from a height of 30 inches. The glass panel did not break. Inspection of the cushioning system revealed little deterioration; the pad on the end of the package-product system which suffered the corner and three edge drops was slightly deteriorated, but significant cushioning potential still remained.

Other Applications. A number of journal articles have presented other applications of alternative cushioning material to replace EPS and other packaging material. For completeness, and to demonstrate additional opportunities for each alternative material, specific applications of alternative packaging materials have been included here.

- "Electronics Challenge: Pack It Safe and 'Green'" summarizes the reasons for the trend towards more environmentally friendly packaging and identifies an application of Hexacomb's kraft-paper product Cushion-Comb to package Epson's ActionNote 700C, their latest notebook computer.[37]
- Barbara McDaniel of Rosemount Inc., incorporated die-cut honeycomb and corrugated kraft paper to protect a uniquely shaped electronic transmitter. This design won the Environmental Award in the 1994 AmeriStar Competition.[38]
- Norel Paper, in conjunction with Enpac developed Enviromold™, a starch-based, biodegradable mold-in-place packaging system which is used to package stereo equipment.[39]
- American Excelsior has designed an effective and efficient protective packaging system out of EcoPlank for a mail-order wine distributer located in California. This distributor replaced its existing EPS design for the more environmentally benign EcoPlank material.
- Another design using EcoFoam pads was presented in a recent issue of *Packaging Technology & Engineering*. "To improve product protection, decrease costs and upgrade aesthetics, Mr. Coffee has switched from corrugated and bubble wrap to American Excelsior's starch Sheets and Planks as an environmentally-sound packaging alternative."[40] Advantages to the new design include a single vendor, anti-static packaging material, and an easily disposable packaging product.

CONCLUSIONS

The results of the technical evaluation reveal the strengths and weaknesses of each protective packaging material. While the results of dynamic tests were utilized in prototype development, the applicability of static, stress-strain tests was not identified. Prototype demonstrations using starch-based foam and layered corrugated pads show the ability of these alternatives to replace EPS as a cushioning packaging material.

Under standard temperature and humidity conditions, dynamic drop test results revealed positive cushioning characteristics of each material. Using samples of 1.5 inch thick, layered corrugated pads offered as much protection as EPS for a single drop; starch-based foam and recycled PE foam displayed lesser protective characteristics. Starch-based foam and recycled polyethylene foam did display a greater ability to absorb the energy resulting from multiple drops than that of EPS. High temperatures and extremes in humidity seem to have the most significant impact on starch-based foam, causing sample deterioration which resulted in decreased cushioning ability.

Test results from dynamic drops (i.e., cushioning curves) were used, in conjunction with design expertise, to develop effective prototype protective packaging designs. EPS, while adequately protecting the consumer product from damage, did not perform to expected levels. Prototype designs using layered corrugated pads and starch-based foam also protected the consumer product from damage, and performed to a level comparable to that of EPS. In applications for glass packaging, starch-based foam prototype designs again revealed positive protective properties of EcoPlank.

CHAPTER 5

ENVIRONMENTAL EVALUATION

The primary objective of the environmental evaluation was to analyze the releases and transfers of 33/50 chemicals resulting from the use of EPS as a cushioning material, and to compare these to the releases and transfers associated with a similar application of the alternative cushioning materials. The use of packaging materials by product manufacturers, however, does not result in the direct release or transfer of the 33/50 chemicals. For example, releases and transfers of the 33/50 chemical benzene will occur during the chemical conversion of benzene into ethyl benzene, but do not occur during the manufacture of an EPS cushioning material or its application in packaging. Therefore, a life-cycle perspective was applied during this environmental evaluation to capture the potential life-cycle emissions of 33/50 chemicals resulting from the use of each packaging material. This life-cycle perspective results in a qualitative and quantitative evaluation of chemical releases resulting from raw materials extraction, processing, and disposal.

The environmental evaluation revealed that most 33/50 chemical releases and transfers occur prior to package manufacturing, use, and disposal. 33/50 chemical releases to the air and water are expected for the pre-manufacturing processes of EPS, starch-based foam, and PE resin (if petroleum is used). The most significant difference identified in the package manufacturing processes was the possible elimination of the VOC (pentane) emission resulting from EPS production; few, if any VOC releases result from either starch-based foam or layered corrugated pad manufacturing. Finally, various disposal options were identified for each material that may be better suited for each material than disposal in a landfill. These results are discussed in detail in this chapter.

PRODUCT LIFE-CYCLE

Life-cycle assessment (hereafter LCA) is a comprehensive concept and methodology for evaluating the environmental and human health burdens associated with a product, process, or activity. The life-cycle of a product includes the basic stages of raw materials acquisition, manufacturing, use/reuse/maintenance, and recycling/waste management. A complete LCA identifies inputs and outputs from each life-cycle stage (inventory); assesses the potential impacts of those inputs and outputs on ecosystems, human health, and natural resources (impact assessment); and identifies opportunities for achieving improvements (improvement assessment).[41]

A complete and comprehensive LCA was beyond the scope of this study. Key life-cycle concepts and issues, however, must be identified and discussed to assess the potential environmental impacts resulting from the application of the evaluated packaging materials. Three broadly-defined life-cycle stages were used to represent the product life-cycles for each packaging material: pre-manufacturing, package manufacturing, and waste management. The remaining sections of this chapter discuss environmental impacts from these three life-cycle stages.

To evaluate the environmental burdens associated with the use of each cushioning material, and to allow a comparison of inputs and outputs between materials, the equivalent use of the material must be considered. When considering cushioning materials in a particular product application, equivalent use can be defined as the amount of each material required to accomplish the same level of production. The equivalent use of each material was determined using the cushion configuration designed for the VCR described in the prototype demonstrations. To maintain the confidentiality of the information gathered from each material manufacturer, however, actual materials use is not explicitly stated in this discussion. Rather, for each VCR packaging system, the quantity of cushioning material used is considered 'one unit' and all inputs and outputs are calculated from that unit.

PRE-MANUFACTURING LIFE-CYCLE STAGES

Pre-manufacturing is defined here as the unit operations that are required to supply raw materials to the package manufacturing life-cycle stage. The primary pre-manufacturing unit operations and resulting environmental releases and transfers are discussed for each material below. The 33/50 chemicals are the focus of the discussion in the pre-manufacturing stage, due to the nature of the packaging materials (i.e., releases occur prior to package manufacturing, use, and disposal).

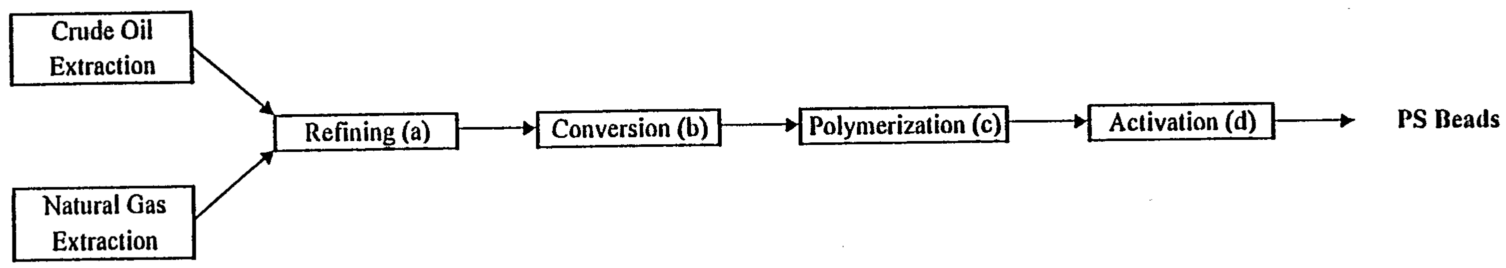
Expanded Polystyrene

Polystyrene resin used in most EPS applications across the country is manufactured from virgin raw materials. Though EPS is a thermoplastic and can be readily recycled, economics has limited its collection and use as a recycled raw material (see Waste Management Life-Cycle Stages below). Therefore, the production of virgin polystyrene resin, presented in Figure 27, represents the pre-manufacturing life-cycle stage for EPS.

Benzene, produced from crude oil, and ethylene, produced from either crude oil or natural gas, represent the chemical raw materials which begin the pre-manufacturing unit operations which produce EPS. Benzene and ethylene react to produce ethyl benzene. Styrene monomer is produced from ethyl benzene and is then polymerized to produce polystyrene (PS) resin. PS resin is combined with a blowing agent, typically pentane, to produce PS beads. The incorporated pentane expands when heated and facilitates the formation of EPS products. PS beads is the raw material which enters the package manufacturing life cycle.

From this pre-manufacturing life-cycle stage, a number of 33/50 chemical releases and transfers can be expected. The production of benzene from crude oil results in emissions of benzene, as well as toluene and xylene, two other 33/50 chemicals which are typically converted to benzene (see Figure 1). The production of ethyl benzene from benzene and ethylene results in benzene emissions as well. Potential emission factors established for these processes support this conclusion; benzene is the top chemical pollutant emitted to both air (1.93 lb benzene to air per ton PS produced) and water (3.79×10^{-3} lb benzene to water per ton PS produced).[42] These values represent controlled emission factors and do not include environmental burdens resulting from energy production and consumption. The production and use of process energies would also contribute to these potential emission factors. The energy requirements to manufacture one ton of PS from raw materials extraction to polymer is 39.4 MBTUs. [43]

FIGURE 27 - PRE-MANUFACTURING LIFE-CYCLE STAGE FOR EPS



Key:
a. Refining - a production of benzene from crude oil, and production of ethylene from natural gas
b. Conversion - production of ethyl benzene from benzene and ethylene, followed by the production of styrene from ethyl benzene
c. Polymerization - production of polystyrene from styrene monomer
d. Activation - production of PS beads by incorporating a blowing agent (i.e., pentane)

Starch-Based Foam Plank

Pre-manufacturing unit operations for starch-based foam include the agricultural production of a starchy crop (e.g., corn or potatoes) and the extraction of starch from this crop. For the purposes of this study, corn will represent the starchy crop. This is consistent with the starch-based foam plank of American Excelsior which is manufactured primarily from modified corn starch. Figure 28 schematically represents the pre-manufacturing unit operations for the production of starch from corn.

The cultivation of corn by typical methods requires the application of chemical additives such as herbicides, insecticides, and fertilizers. Herbicides were applied to 96 percent of the corn acreage in 1995. The most widely used herbicides for corn production in 1995 included atrazine, metolachlor, and cyanazine.[44] Insecticides were applied to 28 percent of the acreage in 1995 with chlorpyrifos and terbufos being the most wide spread. Although these herbicides and insecticides are applied at a low rate relative to the production of corn (e.g., 3.74×10^{-5} lb atrazine/lb of corn harvested [45]), their production processes should be considered as a part of the pre-manufacturing life cycle of the starch-based foam.

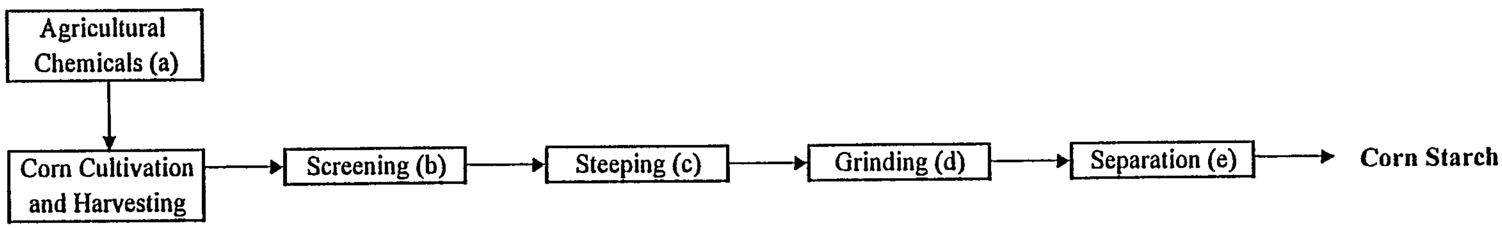
Atrazine is used here to illustrate agricultural chemical production because it is the most widely used herbicide for corn production with use on 65 percent of the reported acreage. Figure 29, a simple flow diagram for the production of atrazine, shows the 33/50 chemical hydrogen cyanide as a chemical raw material in the production process. Information is not available which relates this use of hydrogen cyanide to releases of 33/50 chemicals per ton of starch (or corn) produced. However, it must be acknowledged that this use of a 33/50 chemical exists and releases are possible.

Fertilizers used for corn production include nitrogen, phosphates and potash, and are also major inputs to corn production. Nitrogen, for instance, is typically applied at a rate of about 4.3×10^{-3} lb/lb of corn harvested.[46] Over 95 percent of all commercial nitrogen fertilizer is derived from synthetic ammonia, produced from natural gas; essentially all phosphate is derived from mineral phosphates; potash is a mined potassium salt.[47] The production of these fertilizer inputs are not expected to result in the use or release of 33/50 chemicals.

To plant, cultivate, harvest and dry an agricultural crop such as corn, petroleum fuels and electricity are required to operate heavy agricultural machinery. It has been estimated that 24,000 BTU of energy are consumed per bushel of corn produced.[48] Assuming average corn yields, this translates to a fuel consumption rate of approximately 15 gal of petroleum per acre per year for planting, cultivation and harvesting, and approximately 460 standard cubic feet of natural gas per acre per year for drying. Though direct correlations from this rate of fuel consumption to the quantity of starch produced from corn are not available, it must be acknowledged that the use of petroleum fuels will result in the release of 33/50 chemicals during the refining process, machinery fueling, and possibly combustion.

After cultivation, starch separation from corn kernels is accomplished by the wet-corn milling process. As shown in Figure 28, this process consists of screening, to remove the corn from the cob and other impurities; corn steeping, to soften corn kernels and promote component separation; grinding; and separation, such as centrifugation and cyclone washing, to remove the starch from other kernel components. Wet-corn milling is a water intensive process; 20 gallons of water are required for each 100 pounds of corn processed. Centrifugation and drying are used to remove this water from the final starch product. As a result, wet-corn milling is the second most energy intensive food industry in the United States.[49] The only chemical additive within

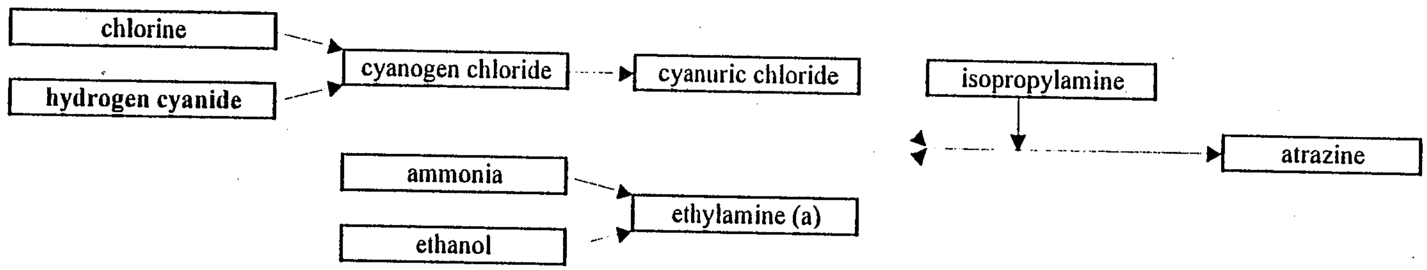
FIGURE 28 - PRE-MANUFACTURING LIFE-CYCLE STAGE FOR STARCH-BASED FOAM PLANKS



Key:

a. Agricultural Chemicals (see figure 29 - Atrazine Production)
b. Screening - removing corn from cob and separating the impurities
c. Steeping - soaking of corn kernels in water to facilitate grinding and subsequent separation steps
d. Grinding - crushing of steeped corn into slurry
e. Separation - separation of corn starch from remaining kernel components via physical separation techniques (e.g., centrifugation).

FIGURE 29 - CHEMICAL FLOW DIAGRAM FOR THE PRODUCTION OF ATRAZINE, A CORN HERBICIDE

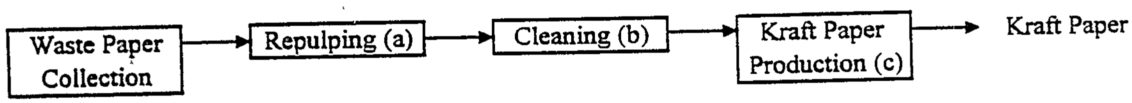


Key: a. Many possible production routes for ethylamine were possible, SRI peer review was used this process scheme is sulfur dioxide in the steeping process; sulfur dioxide controls microbial growth in the aqueous bath and facilitates water absorption into the corn kernel. Therefore, 33/50 chemical releases are not expected from these pre-manufacturing processes of starch-based material.

Layered Corrugated Pads

Layered corrugated pads manufactured by Menasha Sus-Rap are produced entirely of 100 percent post-consumer recycled material. The collection of waste paper thus begins the corrugated pad pre-manufacturing life-cycle chain, as shown in Figure 30. Once wastepaper is received at the paper mill, it is repulped through mixing with heated water in a hydropulper which pulverizes the waste paper, separating the paper fibers and creating a fiber pulp slurry. Through various purification steps (e.g., flotation, centrifugation, and magnetic screening), impurities such as plastics and staples/paper clips are removed from the pulp slurry before entering the kraft paper production process. For corrugated medium, deinking and bleaching is typically omitted from this production process. To produce the desired corrugated characteristics, rosin, alum and starch are added to the pulp slurry during the kraft paper manufacturing process. Chemical processing aids are also added to the slurry pulp to control factors such as foaming.

FIGURE 30 - PRE-MANUFACTURING LIFE-CYCLE STAGE FOR LAYERED CORRUGATED PADS



Key:
a. Repulping - grinding of waste paper with water to create pulp slurry
b. Cleaning - removing impurities such as plastics and metals through floatation, magnetization, and sedimentation
c. Kraft paper production - with the addition of alum, rosin, and starch to pulp slurry kraft paper is produced (Note: Additional processing chemicals may be added)

From this pre-manufacturing process description there are few, if any 33/50 chemical releases to the environment expected.[4] This expectation was supported by facility-specific data collected from a recycled paper supplier to Menasha. Published controlled emission factors for recycled corrugated medium, however, suggest that zinc is the most significant 33/50 chemical emission to water from these processes: 2.15×10^{-2} lb zinc to water per ton corrugated medium produced.[50] This contaminant may be a result of the inks used on the waste paper collected for recycle. The use of zinc and other heavy metals in ink has been greatly reduced over the years; it

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4 For this study, the environmental burdens resulting from the production of paper from virgin wood pulp, and the initial use of paper products, are not considered as part of the burdens of the recycled material. There are methods for allocation of virgin material impacts for recycling loops in the LCA field, but such methods are beyond the scope of this project.

is possible this emission factor reflect such dated information. There are no reported 33/50 chemical emission factors to air.

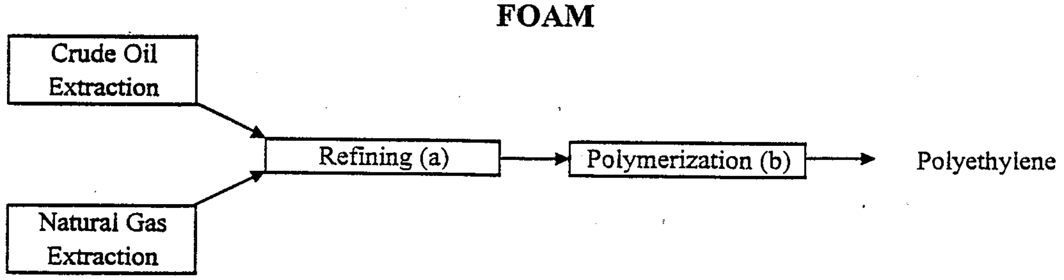
These emission factors do not include environmental burdens resulting from the collection of waste paper for recycling, nor energy production or consumption. The energy required to manufacture one ton of recycle corrugated medium is 17 MBTUs.[51] The production and use of these energy sources could also contribute to the 33/50 chemical emission burden.

Recycled PE Foam

The recycled PE foam evaluated within this study is manufactured from both virgin and recycled material, in a ratio of 80 percent virgin to 20 percent recycled resin (typical ratio for recycled PE foams). To assess the environmental burdens for the pre-manufacturing life-cycle stages, both virgin and recycled polyethylene resin manufacturing activity must be evaluated. For simplicity, however, 100 percent virgin PE resin will represent the produced material in the pre-manufacturing processes for the PE foam evaluated in this study. This assumption most likely over-estimates the emissions resulting from pre-manufacturing processes of recycled PE foam. The use of recycled resin reduces the demand for virgin material, thus reducing crude oil/natural gas extraction and refining burdens. The energy required to process PE resin is less than the energy required to produce virgin resin from natural gas or crude oil.[52]

The pre-manufacturing unit operations for 100 percent virgin PE resin are presented in Figure 31. Ethylene is manufactured from the cracking of ethane, propane, and butane produced from either natural gas or petroleum naphtha. Ethylene is then polymerized under high temperatures and pressures to produce polyethylene resin. As with PS resin production from petroleum feedstocks, emissions of the 33/50 chemicals benzene, toluene, and xylene are expected; no emissions of 33/50 chemicals are expected from the refining of natural gas. Controlled emission factors for the production of low-density polyethylene identify benzene, toluene, and xylene as the only 33/50 chemical emissions to air: 1.80×10^{-1} lb benzene/ton PE; 2.53×10^{-2} lb xylene/ton PE; and 7.00×10^{-3} lb toluene/ton PE. Though benzene and toluene are also emitted to water (1.49×10^{-2} lb/ton, and 1.44×10^{-2} lb/ton, respectively), the 33/50 metal chromium tops the emission factors to water at 3.03×10^{-2} lb chromium/ton PE produced. The production and use of process energy, though not included, would also contribute to these emission factors. The energy required to manufacture one ton of PE resin 39.9 MBTU.[53]

FIGURE 31 - PRE-MANUFACTURING LIFE-CYCLE STAGE FOR RECYCLED PE FOAM



Key: a. Refining - production of ethylene from natural gas or crude oil
b. Polymerization - production of polyethylene from ethylene monomer

PACKAGE MANUFACTURING LIFE-CYCLE STAGES

Facility-specific information was gathered from the manufacturers of three of the cushioning materials. Questionnaires, distributed by mail, introduced each manufacturer to the project, described goals of the environmental evaluation, and gathered data in three primary areas: raw materials, energy requirements, and waste streams. Questionnaires were formatted specifically for each manufacturing process; an example questionnaire is presented in Appendix C, and represents the questionnaire distributed to Tuscarora, the EPS packaging manufacturer for Philips.

Site visits to each manufacturing facility were conducted following the completion of the questionnaires. The purpose of each site visit was to become more familiar with the manufacturing process, to ensure the questionnaire gathered information for the entire manufacturing process, to judge whether the supplied information was reasonable, and to clarify any questions that may result from the interpretation of the completed questionnaires. With this information, facility-specific environmental profiles were developed for each material on a per-unit basis.

Unfortunately, the recycled PE foam manufacturer chose not to participate in the prototype demonstrations or the environmental profiles. Therefore, facility-specific information will not be presented for this material.

EPS Package Manufacturing

EPS is used as the cushioning material in all of Philips' packaging applications. Tuscarora is the sole supplier of this cushioning material for the Philips manufacturing facility in Greeneville, Tennessee. Tuscarora manufactures a number of packaging products including EPS products, corrugated products (both paper and plastic), and EPS-corrugated composites. Data collected by the completed questionnaire and site visit were for the EPS cushion manufacturing operations.

Polystyrene (PS) beads are the raw material entering Tuscarora's cushion manufacturing facility. The beads are delivered in 1,000 lb totes from a BASF production facility located either in Ohio or New Jersey. From these totes, the beads are transferred directly to one of two pre-conditioning units. Pre-conditioning heats the beads with steam causing the encapsulated pentane to expand, thus expanding the PS beads to approximately 50 percent of their final volume in the EPS product (in the final product, PE beads expand nearly eight times their original size). By controlling the amount of heat delivered, and therefore the amount of expansion, the density of the final EPS product is controlled. The pre-conditioned beads are then stored for a short time (i.e., less than 12 hours) in large equalization hoppers, where they are drawn off and delivered to the molding process units.

At Tuscarora the molds which form the desired cushioning configurations are fabricated out of aluminum and coated with a non-stick layer of Teflon®. The aluminum molds are hollow, allowing water to pass through the inner core of each unit to cool the molded EPS product. Pre-conditioned PS beads are injected into the cushioning configuration molds along with steam. The delivered steam bonds the beads together and completes the bead expansion process by heating the polymer and expanding the remaining pentane encapsulated in the beads. The continuous, closed-loop flow of water cools the EPS product before it is removed from the mold. This entire process is automated and computer controlled; manual labor is used to change the aluminum molds and to stack and pack the EPS products ejected from the processing units.

According to Tuscarora's representative, these EPS molding units are the largest in the world and represent a unique advancement in the EPS molding industry. Typical EPS molding processes use stainless steel molds, the application of steam within the core of the mold to heat the injected beads and complete the expansion process, and the application of cooling water into the same mold core to cool the product prior to extraction. Each cycle of the process heats the mold to 105 °C, followed by a rapid water-cooling step to a mold temperature of 88 °C. This typical EPS molding process is slow and energy intensive. The combination of the Teflon® coated aluminum molds, steam delivery solely to the PS beads, and continual closed loop cooling with water used in Tuscarora's molding operation reduces energy use and water consumption by 25 percent when compared to the typical process units.

Table 9 presents Tuscarora inventory data developed from the completed questionnaire and facility site visit. To maintain confidentiality, the information is presented in terms of equivalent use (i.e., the quantity of material required to protect a VCR).

TABLE 9 - INVENTORY OF INPUTS AND OUTPUTS FOR EPS CUSHION MANUFACTURING

Category	Input or Output	Quantity
Raw Materials	EPS Beads (e/pentane)	one unit
	EPS Regrind	1.29 g/unit (2.8 x 10^{-3} lb/unit)
Energy Requirements	Electricity	0.101 kW-hr/unit (3.45 x 10^{2} BTU/unit)
	Natural Gas	1.52 x 10^{-5} SCF/unit (0.03 BTU unit)
Wastes	Solid, Non-Hazardous Waste	1.42 x 10^{-7} lb/unit
	Hazardous Waste	0
	Wastewater	8.20 x 10^{-3} gal/unit (0.01 lb/unit)
	Air Emissions	2.45 g/unit (5.4 x 10^{-3} lb/unit)

The solid waste generated during the manufacture of EPS packaging contains primarily waste EPS (e.g., loose beads and broken EPS parts) and process wastes such as miscellaneous boxes, shrink wrap, and binding twine. A small percentage of the waste EPS is incorporated as regrind back into the packaging products. The remaining wastes are disposed of at a local municipal solid waste (hereafter MSW) landfill. The wastewater, primarily condensate water from the boilers used to heat the various process units with steam, is disposed of down the sewer drain where it enters the local Publicly Owned Treatment Works (hereafter POTW). No data were available on the composition of the wastewater. Finally, the air emissions from the process are exclusively pentane emitted from the EPS beads during the expansion process.

Starch-Based Foam Package Manufacturing

American Excelsior's facility in Lonbard, Illinois is currently the only location manufacturing the Eco-Plank cushioning product. The starch raw material is delivered to this facility in 2,000 lb totes via rail or tractor-trailer trucks from National Starch (a division of Unilever) located in Bridgewater, New Jersey. From the totes, the starch is transferred to hoppers which gravity-feed the starch into the primary processing unit. This primary unit is a horizontal-screw extruder, similar to those typically used in the food processing industry. Starch is delivered to one end of the extruder. The horizontal screw moves the starch along the length of the unit while mixing in water and a small amount of soybean oil under conditions of elevated temperature (near 150 °C) and pressure. A continuous starch-based foam sheet is formed when the starch mixture is forced through a small plate opening in the opposite end of the extruder, causing the water to instantly vaporize into steam when exposed to atmospheric/ambient conditions. This sheet has a fluted appearance (or S-shape) as a result of the shape of the plate opening.

The continuous foam sheet leaving the extruder is cut to length by a guillotine cutter and enters a series of rollers. A thin layer of water-based, starch adhesive is added to one side of the sheet at the final roller. The individual sheets are then manually stacked to assemble the standard planks. Foam sheets are combined in this manner until enough layers have been combined to produce a plank of the desired thickness. The plank is then passed through a conveyor system which compresses it slightly to ensure adequate contact between layers and consistency in plank thickness. Planks can range in thickness from a single foam sheet of 1/4 inch to any thickness in 1/4 inch increments; the standard plank manufactured is 2 inchs thick. Sheets of lesser thickness which are not fluted are also possible. Cushioning products are produced by manually cutting various shapes from these planks and assembling them into the appropriate configuration. Table 10 summarizes the inventory input and outputs for this process, based on equivalent use (i.e., the quantity of material required to protect a VCR).

TABLE 10 - INVENTORY OF INPUTS AND OUTPUTS FOR STARCH-BASED FOAM PLANK MANUFACTURING

Category	Input or Output	Quantity
Raw Material	Starch	one unit
	Water-Based PVA Adhesive	9.9×10^{-3} gal/unit (8.3×10^{-2} lb/unit)
	Soybean Oil	8.89 g/unit (2.0×10^{-2} lb/unit)
	Other Additives (e.g., talc)	1.55 g/unit (3.4×10^{-3} lb/unit)
Energy Requirements	Electricity	1.37 kW-hr/unit (4.7×10^{3} BTU/unit)
	Natural Gas	0
Wastes	Solid, Non-Hazardous Waste	9.4×10^{-2} lb/unit
	Hazardous Waste	0
	Wastewater	1.02×10^{-2} gal/unit (8.54×10^{-2} lb/unit)
	Air Emissions	0

The wastes resulting from the manufacture of starch-based foam materials are minimal. The non-hazardous, solid waste stream, which dominates the outputs from American Excelsior, consists of waste starch material, as well as other process debris such as empty containers, bags, and twine. This material is disposed of at a MSW facility. The wastewater effluent consists of non-contact water used to heat the extruder, which is drained during each process shut-down. This wastewater is discharged to the sewer and is treated by the local POTW; composition data on this wastewater were not available. American Excelsior data identified no other waste streams resulting from the manufacturing process of Eco-Plank.

Layered Corrugated Package Manufacturing

Facility-specific information was made available for the Menasha Sus-Rap Danville, Virginia manufacturing facility. A questionnaire was completed by Menasha and a site visit was conducted. Table 11 summarizes raw materials use, energy consumption, and waste generation for the manufacturing operations based on equivalent use (protective packaging for one VCR). A description of Menasha's manufacturing process for layered corrugated pads and a discussion of the materials inventory is presented below.

TABLE 11 - INVENTORY OF INPUTS AND OUTPUTS FOR CORRUGATED PAD MANUFACTURING

Category	Input or Output	Quantity
Raw Material	Layered Corrugated Pad	one unit
	Starch-Based Aqueous Adhesive	9.7×10^{-3} gal/unit (8.1×10^{-2} lb/unit)
	Water-Based PVA Adhesive	1.3×10^{-2} gal/unit (0.11 lb/unit)
Energy Requirements	Electrical	3.5×10^{-4} kW-hr/unit (1.2 BTU/unit)
	Natural Gas	2.6×10^{-2} SCF/unit (26.4 BTU/unit)
Wastes	Solid, Non-Hazardous Waste	3.2×10^{-2} lb/unit
	Hazardous Waste	0
	Wastewater	1.1×10^{-5} gal/unit (9.2×10^{-5} lb/unit)
	Air Emissions	0

Menasha Sus-Rap manufactures three standard cushioning pad products: channel pads ("u"-shaped), angle pads ("v"-shaped), and flat pads (plank-type pads similar to those used as test specimens in the technical evaluation of this project). One process line is devoted to the production of channel pads, two process lines are devoted to the production of angle pads, and one process line is devoted to the production of flat pads. One corrugation line supports all four product process lines. The kraft paper used to manufacture the various pads is made of 100 percent post-consumer recycled material. Raw materials - paper and glues - are delivered by tractor-trailer truck and stored on the process floor prior to use. Paper products are received in rolls; glues are received in 250 gallon totes.

The pad manufacturing process begins with the production of a single-sided corrugated sheet, or single-facer - a flat sheet and a fluted sheet of paper bonded together. Two rolls of paper are properly positioned and fed into the corrugation process unit. The corrugation process unit then forms the flutes in one sheet, applies a water-based, starch adhesive between the sheets, and presses the sheets together while applying steam to promote adhesion. Paper weights can vary depending on the desired properties of the final product; typical paper weight is 26-pound kraft paper. Paper width is also dependant on the final product.

The single-facer is then spooled into a roll for use in the flat pad or channel and angle manufacturing processes. When spooled for channel and angle manufacturing processes, the single-facer is first cut into four- to six-inch strips which run the length of the paper. Waste paper trimmed from the sides of the single-facer during the cutting process is pneumatically conveyed to a compactor where it is baled and sent off-site for recycling.

Within the flat pad manufacturing process, any number of single-facer layers are combined to create a pad that varies in thickness from 1/4 inch to 2 inches. From free-moving rolls, the single-facer layers are pulled through glue application rollers where beads of water-based, vinyl acetate adhesive are applied. A conveyor system which pulls the layers through the glue application system (and pushes the formed pad out) also compresses the layers to promote glue adhesion and a consistent pad thickness. After compression, the pads are cut to standard length, stacked, and stored for final processing.

A similar system is employed to combine the various single-facer layers to produce the channel and angle pad products. Two to eight single-facer layers are typically combined using beads of water-based, vinyl acetate adhesive. A conveyor system pulls the layers through the glue application units, compresses the pads, and pushes the pads to the cutting station. The pads are cut to length (typically three feet) either by a continuous guillotine-style cutter or a saw which interrupts the movement of the pad. Each pad section is then folded into the channel or angle shape. The pads are then stacked for final processing.

Final processing of the pads includes scoring, notching, or stamping. Scoring of a pad allows customers to size the product as desired; notching and stamping allows the angle and channel pads to bend around corners. Flat pads are cut to various sizes depending on customer requirements. Other features that can be incorporated into the production process include the following:

- Single-facer layers can be scored every inch to allow customers to precisely size a standard pad to a desired and specific size.
- A fabric-lined single-facer layer can be included on the inside surface of the pads to protect abrasion-sensitive product surfaces.
- Printing on one outer surface of the pad is a recently added feature to Menasha's pad products. Red or black print can be applied in simple designs (e.g., recycle symbols or product identification numbers).

The various waste streams generated in Menasha's manufacturing facility include a solid, non-hazardous waste and wastewater. The solid non-hazardous waste is primarily scrap paper and formed corrugated products which is baled and returned to their kraft paper supplier for reprocessing. Other solid wastes which may be generated, including bags, twine and rubbish, are disposed of at a MSW landfill. The wastewater generated during the manufacturing process is a result of purging and cleaning the glue lines of each assembly line. The water used for this cleaning operation is collected in the empty glue totes and returned to the vendor for disposal or reprocessing. The wastewater contains 85 percent water and 15 percent glue; equal quantities of each glue (starch-based and poly vinyl acetate) are assumed to be present in the wastewater.

WASTE MANAGEMENT LIFE-CYCLE STAGES

Various waste management options are available for each of the cushioning materials evaluated in this study, from reuse and recycling to composting. Waste disposal options available to each of the cushioning materials are presented in Table 12. Typical waste management practices dispose of packaging material along with other MSW destined for landfill. The continual decline of available landfill space, however, was the primary cause for the public's demand for more environmentally benign packaging.

TABLE 12 - POSSIBLE WASTE MANAGEMENT OPTIONS					
	Landfill	Energy Recovery	Recycling	Composting	Water Dissolution
EPS	✔	✔	✔		
Starch-Based Foam	✔			✔	✔
Layered Corrugated	✔	✔	✔	✔	
Recycled PE Foam	✔	✔	✔		

Figures for 1993 show that there are an estimated 207 million tons of MSW generated per year in the United States.[54] That same year, the number of landfills accepting MSW was 4,482, down from 8,000 in 1988. By 1994, the number of operating landfills had dropped to 3,558.[55] Some closures were due to the more stringent standards for design, operation, and closure of MSW landfills adopted by the U.S. EPA in 1991.[56] Other landfills closed because they reached capacity. While packaging wastes contribute to this landfill burden, there are more appropriate waste management options that can be selected which would optimize both costs and benefits. The following discussion presents selected options for each material, and evaluates the potential national impacts resulting from them.

Expanded Polystyrene Waste Management Options

Polystyrene is a thermoplastic and is therefore 100 percent recyclable. The manufacturers, raw material suppliers, and equipment manufacturers of polystyrene are trying to take advantage of this fact, while reducing the burden of the nation's landfills. In 1989, the polystyrene industry created the National Polystyrene Recycling Company (hereafter NPRC) which established four major recycling centers. Since then, commercial recyclers have been establishing regional recycling centers to serve both communities and businesses.[57] In July 1991, more than 80 companies, representing every major manufacturer of EPS protective foam packaging, joined together to form the Association of Foam Packaging Recyclers (hereafter AFPR). Later that same year, the AFPR and Polystyrene Loose-Fill Producers Council announced the formation of programs for collection sites nationwide that are accepting shape-molded protective packaging and loose-fill peanuts for re-use and recycling. Programs to recycle polystyrene now exist in over 25 states.[58].

The reuse and recycle of EPS foam can greatly reduce environmental burdens resulting throughout the products life. Using the same material multiple times in similar applications also postpones its entry into a waste stream destined for landfill. Incorporating regrind into EPS products can consume process waste that would typically enter the solid waste stream, while reducing the demand for PS resin. Also, reprocessing of EPS material can save nearly 80 percent of the energy typically consumed to produce PE resin from virgin raw material sources (i.e., petrochemical feedstock).[59]

It is essential, however, that large quantities of EPS wastes are collected to make reuse and recycling cost effective. This fact has been one hurdle which the associations and councils are continually battling. The low density of EPS material limits its efficient transport over long distances. To alleviate this potential problem, AFPR collection sites and associated facilities are located across the country. Nationally, few municipal recycling programs support the collection of EPS; some do support the collection of crystalline polystyrene. From a life-cycle perspective, the benefits gained by recycling and reusing EPS, as with any material, should be weighed against the energy use and emissions resulting from its transport.

Starch-Based Foam Waste Management Options

Two waste management options most appropriate for starch-based foam take advantage of their biological origin. The two options are composting and dissolution in water prior to discharge, preferably to a POTW. Composting can take place in the consumer's back yard along with yard trimmings and kitchen organic material, or take advantage of municipal compost programs being established throughout the country. Dissolution of starch-based foam packaging in water places an additional 'disposal' or treatment burden on local POTWs, but offers another disposal option available to the consumer.

Municipal compost programs are being established across the country to offer an alternative waste management option for organic material typically entering landfills. The vast majority of this nation's programs focus on a single material, yard trimmings waste, while a small fraction accept and manage mixed MSW. In 1994 there were 3,202 yard trimmings composting facilities reported nationwide,[60] while only 17 MSW composting facilities were operating that same year.[61] By March 1996, the number of yard trimmings compost facilities rose to over 4,000 and 22 additional MSW composting facilities were in various stages of planning, permitting, construction, and pilot testing.[62] These figures and programs do not consider home/backyard composting.

The dissolution of starch-based foam in water is the second option available to the consumer for the disposal of this protective packaging. This disposal option would result in an added biological oxygen demand (BOD) in municipal wastewater which typically enters a POTW. The impact of this higher BOD is expected to be minimal for two reasons. First, the literature BOD values for starch are around 0.75 lb BOD per lb starch. Even if large quantities of EcoPlank are used in a particular packaging application, the dissolution of that material in water will contribute insignificantly to local POTWs. Second, the distribution of protective packaging is expected to be extensive enough to minimize the potential for concentrated applications of the product. The relative insignificance of these impacts are supported by the "1992 Needs Survey Report to Congress," completed by the U.S. EPA.[63]

Layered Corrugated Waste Management Options

Packaging recycling is gaining popularity as federal, state, and local initiatives continue to support its growth. In the late 1980's, the U.S. EPA set national goals for MSW recycling. In 1994, the 24 percent rate of MSW recycling fell just short of the national goal of 25 percent.[64] More than 40 states have implemented similar goals and mandates. For example, the Massachusetts legislature passed a bill mandating recycling and recycled content of specified packaging materials.[65,66] Industries and industry associations have also set goals and mandates for recycling and recycled content packaging. Recycling is now available to more than 100 million United States citizens through curbside programs, drop-off centers, and buy back centers.[67]

Corrugated material is the highest recycled material, by weight, in the nation.[68] Industry sources contribute most to the corrugated recycle stream - more than 60 percent of the commercial sources of recycled corrugated material. Residential sources of corrugated material to the recycle stream are extremely low - less than one percent.[69] However, the existing national infrastructure for residential recycling offers the potential to expand current residential corrugated recycling efforts.

"The 'success' of recycling schemes is usually judged in terms of the participation rate and the quantity of material diverted from the waste stream. However, there is also a need for an evaluation of the environmental and social impacts associated with the collection and transport of recyclable materials."[70] No attempt was made, either in this study or the Tellus Packaging Study previously mentioned, to assess, either quantitatively or qualitatively, the environmental burdens associated with the collection and transport of recycled materials. As presented under the recycling options of EPS, transportation can significantly reduce (possibly overshadow) the environmental benefits of recycling. Transportation distances and the utilization of space in collection vehicles are key factors that will influence the benefits and costs of recycling any material.

Recycled PE Foam Waste Management Options

Based on the results of the technical evaluation, recycled PE foam exhibited characteristics ideally suited for returnable/reusable packaging applications. The concept of reusable distribution packaging is not new. Automobile manufacturers have demanded the use of returnable packaging by their suppliers. The application of reusable packaging in the consumer products industry, however, has been limited. This limited application may be a result of a lack of information, an infrastructure that would support a reusable packaging program, and/or product standardization. National and international regulations concerning consumer product packaging, however, may spur additional interest and information regarding returnable packaging.

If planned, organized and implemented properly, a returnable/reusable protective packaging system can offer cost benefits and improve customer relations. Four features of reusable packaging systems, presented in Table 13, have been identified. Also presented in Table 13 are some obstacles which limit the implementation of returnable/reusable packaging and several options which could promote the implementation.

As presented in Table 13, short distances, frequent deliveries, small number of parties and company-owned vehicles are the optimal features of an effective returnable/reusable packaging system. Shorter distances mean lower return costs and a quicker return of containers to the supplier. Frequent deliveries is closely tied to the rate which products are used/sold. If containers are emptied quickly and frequent deliveries are required, storage space for empty containers is minimized and the quantity of returnable containers in circulation is reduced. Controlling the return of empty containers is easier when the number of parties handling containers is small. Company-owned vehicles typically travel between a limited number of manufacturers/suppliers and customers. Once a shipment is delivered, the dedicated line typically returns to the manufacturer for another trip. This dedicated line thus simplified travel logistics and costs.

TABLE 13 - FEATURES, OBSTACLES, AND PROMOTION OPTIONS FOR RETURNABLE/RECYCLABLE PACKAGING SYSTEMS		
Features	Obstacles	Promotion Options
Short distribution distances Frequent deliveries Small number of parties Company-owned or "dedicated" distribution vehicle	Large initial capital expense Cost of tracking and accounting for containers Cost of returning containers to point of origin Lack of storage space for empty containers Resistance to change on the part of suppliers, distributors, and customers	Third-party leasing of containers Company/Industry-wide standardization Cooperative efforts between producers, suppliers, distributors, and customers Designing containers to be easily stacked, stored, and reused Government procurement guidelines that favor reuse

Source: David Saphire. "Delivering the Goods - Benefits of Reusable Shipping Containers." INFORM, Inc. 1994.

CONCLUSIONS

The use or release of 33/50 toxic chemicals is not a direct result of either package manufacturing or package use for the materials evaluated in this study. To assess the use and release of 33/50 chemicals resulting from the use of each material, a life-cycle perspective was taken for the environmental evaluation. With this perspective the use and release of 33/50 chemicals, along with other chemicals/releases of concern, was identified. Table 14 summarizes these findings for each material for each of the three broad life-cycle stages evaluated: pre-manufacturing, package manufacturing, and waste management.

The release of 33/50 chemicals was identified in the pre-manufacturing life-cycle stages for all packaging materials. For the production of PS, benzene emissions to air and water predominate all chemical releases to the environment. For the cultivation and processing of corn to make the starch-based packaging materials, the use of 33/50 chemicals is limited to the production of specific agricultural chemicals. Though agricultural chemicals are used throughout the industry, the associated 33/50 chemical emissions is assumed to be minimal.

Insignificant 33/50 chemical releases are expected from the pre-manufacturing processing steps required to produce recycled layered corrugated materials. Though zinc was identified as the primary emission (i.e., emission factor) to water, this metal is assumed to be a contaminant of the waste paper and has been significantly reduced in recent years with ink replacements. Finally, the production of PE foam also required petroleum refining, resulting in the emission of benzene to both air and water. The reported emission factor for chromium to water, however, was the most significant 33/50 chemical release. Process energies are not reflected in these emissions.

TABLE 14 - SUMMARY OF ENVIRONMENTAL EVALUATION, LIFE-CYCLE PERSPECTIVE

Packaging Material	Pre-Manufacturing[1]	Package Manufacturing (Facility-Specific Data)	Waste Management
EPS	Benzene, toluene, and xylene releases result from the production of benzene; benzene releases occur during the production of ethyl benzene for styrene. Energy requirements: 39.4 MBTU/ton	VOC (pentane) emissions to air are significant. Energy requirements: 345.03 BTU/unit	EPS, as a thermoplastic, is recyclable, but the recycling infrastructure is limited.
Starch-Based Foam Plank (corn based)	The production of specific agricultural chemicals applied to corn crops require the use of 33/50 chemicals (e.g., hydrogen cyanide). Release of these chemicals can be expected. Energy requirements: 15 gal/acre/yr petroleum; 460 scf/acre/yr natural gas (2.4×10^3 BTU/bushel)	Few emissions to air or water. Energy requirements: 4700 BTU/unit	Composting or dissolution in water minimizes landfill burdens and utilizes natural characteristics or the material.
Layered Corrugated Pads	No significant 33/50 chemical releases are expected from the reprocessing of waste paper into corrugated medium. Releases to water of other pollutants (e.g., BOD) may be significant. Energy requirements: 17 MBTU/ton	Few emissions to air or water. Energy requirements: 27.6 BTU/unit	Recycling practices utilizes existing corrugated recycling infrastructure which minimizes landfill burdens.
Recycled PE Foam	Benzene, toluene, and xylene emissions result from the refining of petroleum as a feedstock. These emissions are eliminated if natural gas is used as the primary feedstock. Recycled resin reduces release and energy use as compared to virgin PE. Energy requirements: 39.9 MBTU/ton	No data.	Implementation of reusable/ returnable packaging utilizes the superior cushioning characteristics of PE foam, reduces material consumption, and reduces landfill burdens.

[1] 33/50 chemicals were the focus of the Pre-Manufacturing life-cycle stage due to the nature of the packaging materials.

Within the facility-specific package manufacturing stage of each product's life cycle, the most significant differences are energy consumption and the release of VOCs to air. The manufacture of layered corrugated pads consume the least amount of energy and result in few emissions to air or water. The release of the blowing agent pentane (a VOC to air) represents the most significant environmental burden reported for the production of EPS packaging. Energy requirements for the production of starch-based foam plank dominates the environmental profile for this material within this life-cycle stage. Similar data for a PE foam package were not available; PE foam manufacturers chose not to participate in the demonstration of their packaging product in an electronic consumer product application.

Finally, various waste management options for each packaging material were evaluated. Current land disposal of all packaging waste does not utilize characteristics inherent in the material. EPS is a thermoplastic, and as such is readily recyclable. Tests have shown EPS packaging, manufactured from recycled PS resin and renewed blowing agent, performs as well as virgin EPS. A cost effective and efficient nationwide collection system, however, must be further developed. The nature of starch-based foam plank makes it ideal for composting; dissolution in water which then enters the POTW is also a viable option. Layered, corrugated pads can enter existing recycle infrastructures across the country, and reuse/return options for PE foam will utilize the superior cushioning characteristics of this material. Each option removes a burden from the MSW stream and the landfill capacity of the nation. Each option also reduces the need for virgin raw materials and thus reduces the resulting emissions.

This comparison of environmental profiles has not considered the toxicity of the pollutants/contaminants, nor their persistence in the environment and impact on human health and the environment. For example, benzene is a proven human carcinogen, but degrades quickly in the environment. The impacts of energy consumption and transportation requirements have also been omitted from this evaluation. Transportation requirements may represent a significant contributor to the environmental burdens when considering the collection requirements of recycled materials. When considering the potential shift in environmental loadings between selected materials, these issues must also be considered.

CHAPTER 6

ECONOMIC EVALUATION

The cost of packaging is not merely the cost of materials and the expenses incurred during the manufacturing process. Costs can also be measured in terms of package-product assembly time, labor requirements, consumer values, distribution burdens, and more. The economic evaluation of this chapter attempts to address many of these cost parameters which must be considered in packaging design, distribution, and sales. Quantitatively, the cost of materials and manufacturing are assessed for EPS and each of the prototype designs. An assessment of the additional cost parameters is accomplished qualitatively, identifying possible benefits and burdens associated with each material and design.

Within identical packaging applications, assuming all other parameters are equivalent, layered corrugated pads were the most cost competitive packaging alternative when compared to EPS. Through 37 percent more expensive than EPS, layered corrugated pads were more cost competitive than starch-based foam (which was over 400 percent more expensive than EPS). Similar cost comparisons were not available for recycled PE foam.

MATERIALS AND MANUFACTURING

For many consumer-product manufacturers, the acquisition of packaging materials (in their raw state) and the manufacture of desired cushioning configurations are accomplished through contract manufacturers. Just as Tuscarora manufactures EPS protective packaging for Philips, Menasha and American Excelsior satisfy the packaging demands of their customers. Thus, the costs of materials and manufacturing are reflected in the purchase agreements established between supplier and customer.

To compare the costs of the alternative packaging materials to those of EPS, price quotes were requested from each packaging manufacturer. Two cost comparisons are presented below. First, a cost comparison is presented for EPS end caps and the VCR prototype designs for starch-based foam and layered corrugated pads, which were presented in the Technical Evaluation. Secondly is a more general evaluation of the costs and benefits MAYTAG could experience if their current packaging configuration for glass panels is replaced by the demonstrated prototype designed by American Excelsior.

Comparison of Costs - Philips' VCR

American Excelsior and Menasha Sus-Rap were each asked to supply a cost quote for the VCR prototype packaging design demonstrated above in the technical evaluation. Philips was also asked to supply the cost of their current EPS packaging. The parameters used to establish the cost estimates and a comparison of the cost quotes are discussed below for each material.

Expanded Polystyrene. Though manufactured and packaged elsewhere, Philips' cost for a set of EPS end caps (i.e., a packaging unit) was estimated using the weight of the material (one set of end caps), the end caps engineering shape, and the application of established conversion factors. The conversion factors take into consideration the holes, indentions, and protrusions of the cushioning product, each of which contribute to the cost of the packaging system. From this calculation, Philips' estimated cost for a set of end caps was $0.40 per unit. This price does not reflect the cost of the corrugated box.

Starch-Based Foam. The cost for the starch-based foam prototype includes the quantity of material consumed by the design, both starch-based foam and corrugated substrate, as well as the labor costs associated with cutting and assembling the passing prototype design. The costs of the EcoPlank prototype design was quoted at $2.35 per unit.

Layered Corrugated Pads. To estimate the cost of the layered corrugated prototype, Menasha considered the thickness of the pad (i.e., number of layers), weight of paper used (e.g., 26 # kraft), whether the design consists of flat pads, corner pads, or channel pads, as well as labor requirements such as notching and assembly. The estimated prototype cost using this information was calculated to be $0.57 per unit for 1,000 units and $0.55 per unit for 10,000 units.

Comparison of Costs - Philips' VCR. Each cost estimate presented above was completed in isolation, with no direct knowledge of the competitor's price or the quantity of units desired. The estimated costs for the layered corrugated prototype was the most cost competitive when compared to the EPS packaging; the estimated price was 30 percent ($0.17) more per unit than the current EPS system.

Starch-based foam is considerably more expensive; the unit price for the EcoPlank prototype is six times the price estimated for EPS. It should be noted, however, that EcoPlank is an emerging product, as EcoFoam loose-fill was six years ago. Tracking the cost per cubic foot of EcoFoam loose-fill reveals a decrease of nearly 50 percent over the last six years. This cost decrease can most likely be attributed to the establishment of a secure market, process optimization, and economies of scale. A similar decrease in cost can be expected for EcoPlank as the market becomes more established and American Excelsior takes advantage of economies of scale. A 50 percent decrease would still place the price of EcoPlank above that of layered corrugated and EPS. The benefits identified below may contribute to cost justifications.

Comparison of Costs - MAYTAG's Glass Panel

MAYTAG's current packaging configuration for the tested glass panel includes a combination of plastic bubble wrap and crushed paper which surrounds the product in a corrugated shipping box. The cost of this packaging design is $0.65 per package/product system (includes box and protective materials). This cost is low when compared to that of the starch-based prototype design which was estimated to be $4.80 per package/product system (includes starch-based foam and box).

There are, however, additional costs associated with the current packaging design which must be considered when comparing the two packaging systems. The current packaging configuration for glass panels results in a ten percent damage rate of the product. Damaged products cannot be repaired and must be replaced. This results in three additional costs. First, the damaged panel must be properly disposed of; as MSW landfill tipping fees continue to increase, this disposal cost becomes less significant. The second cost resulting from the damaged shipment is that of the part itself. The glass panel tested in this project has a retail value of over

$180. Finally, to replace the damaged part, a second part must be packaged and delivered, resulting in additional material costs and shipping fees.

The starch-based prototype clearly showed effective protective properties during the technical drop test series. If additional tests on the prototype design and current configuration show superior protective properties offered by the prototype, the costs of panel replacement and disposal would be eliminated. Such considerations must be assessed when alternative packaging configurations/materials are considered to replace ineffective packaging systems.

ADDITIONAL COST PARAMETERS

There are a variety of general cost parameters which describe the options and issues that must be considered for packaging design. These cost parameters include the following: capital equipment costs, packaging line productivity, distribution costs (including the possibility of returnable/reusable packaging), and consumer value. These costs are briefly discussed below.

Capital Equipment Costs

The capital equipment costs for the manufacture of packaging is strongly tied to the packaging material selected. The use of molded EPS as a protective packaging material requires the design and manufacture of new process molds each time the package design changes; rather than change the manufacturing process equipment, the assembly requirements for layered corrugated pads and starch-based foam changes as design configurations change. This difference and the resulting costs may impact the selection of materials used for protective packaging.

Using the VCR EPS end caps as an example, the tooling costs to manufacture new molds can range from $1,000 for a typical design, to $10,000 for the Teflon®-coated molds. For reasons of capital cost depreciation, these tooling costs are not typically included in the prices quoted by packaging suppliers, and are not included in the cost estimate presented above for Philips' end caps. Each time Philips changes a packaging design, mold tooling is an additional cost that must be included in the overall packaging costs.

In contrast to this, both starch-based foam and layered corrugated pads, though limited in the possible configurations, offer a diverse application base using the same process equipment. Flat and channel pads can be formed and combined in ways to accomplish a variety of design configurations, even as the package and the product designs change. The costs of assembly labor must be considered and is typically included in cost quotes from packaging suppliers. Starch-based foam planks and layered corrugated pads may therefore offer more flexibility and save money when considering capital investment requirements.

Packaging Line Productivity

Productivity is an issue concerning both the packaging supplier and the product manufacturer responsible for assembling the product and package together into the distributed product-package system. Productivity from the standpoint of the package manufacturer and the product manufacturer is briefly discussed here.

To support product manufacturers, the package manufacturer must be able to supply a continuous and consistent flow of protective packaging units. For example, a single product manufactured by Philips in Tennessee has a production rate as high as 1,500 units per shift. At this time, neither Menasha Sus-Rap nor American Excelsior could support this production rate. This, however, does not mean that given the opportunity, neither Menasha Sus-Rap nor American Excelsior wouldn't expand current production to meet the new demand. Not all consumer product manufacturers have such a high production rate. Other outlets for alternative packaging, such as mail-order services, are also available. MAYTAG represents such an application of alternative materials; multi-pack units are repacked individually and distributed to various locations across the country. Economy of scale and productivity are expected to increase for EcoPlank as the product becomes established in the market. Based on current packaging trends (see Consumer Values below), layered corrugated pads, though used extensively in a variety of furniture applications, may see increased application in consumer electronics resulting in greater production capacities.

Packaging costs, beyond those of material costs, accrued by product manufacturers are a result of materials management and product-packaging assembly processes. The packaging design can influence both of these manufacturing packaging costs. Packaging systems that consist of as few parts as necessary represent one way in which assembly costs can be minimized. Fewer parts per product-package system simplifies packaging inventory requirement (i.e., materials management). In addition, assembling fewer parts around a product simplifies labor burdens, possibly shortening assembly time and reducing labor costs. Another packaging design consideration is that of 'ease of manipulation.' If a packaging system is easy to manipulate around the product, the assembly system may be simplified and assembly time reduced. Optimization such as this, of the product manufacturing process, can be observed in recent modifications to the Philips' manufacturing process facility. Philips has automated portions of the product-packaging assembly process to help optimize the entire manufacturing process. The current protective packaging design (two end caps) works well with this automated system and was a result of process optimization.

Distribution

Cube Efficiency. The issues of distribution costs were avoided in the VCR prototype designs by placing the restriction of box size on the developed designs. As stated above, Philips has optimized the volume available in all modes of transport (semi, rail, air); this optimization is known as "cube efficiency." Stacked products consume as little space as possible, while balancing the various sizes between products. By placing box size restrictions on the prototype designs, the optimal use of space was not lost.

The size of the package-product system, however, must be considered when developing a new packaging design for a product. If the package-product systems are distributed individually, as in the case of MAYTAG, optimizing weight and material usage may influence cost more than size. The costs associated with the distribution of multiple package-product systems, however, can be greatly influenced by system size. Furthermore, the less-than-optimal use of transport space may result in greater environmental burdens associated with increased transport requirements.

Reusable/Returnable Packaging. A completely separate discussion of distribution costs is required when product manufacturers and packaging designers consider returnable/reusable packaging. The benefits and costs of reusable packaging are clearly presented in the INFORM publication, *Delivering the Goods - Benefits of Reusable Shipping Containers*.[71] Hypothetical scenarios and actual case studies are presented in the publication. One hypothetical scenario focuses on corrugated boxes, and shows the possible cost savings that could result from packaging reuse:

> A company that makes shipments in single-use corrugated boxes can cut the quantity of container material needed for 1 million shipments by 50 percent if it uses those boxes twice; by 70.6 percent if it ships its products in reusable boxes that can be used five times; and by 98.5 percent if it switches from single-use corrugated boxes to plastic containers that can be used 250 times.[72]

The use of returnable/reusable packaging incurs unique costs as well. These costs are either the responsibility of the product manufacturer or the packaging designer, depending on who is responsible for managing the returnable/reusable packaging. These unique costs include return transportation to bring the returnable packaging back to a location where it can be reused, and packaging inspection, maintenance, and reprocessing. Standardization of package and product design can simplify the application of a reusable package, and make its application much more cost effective. Packaging reuse is discussed further in the next chapter.

As previously mentioned, recycled polyethylene foam is suited for returnable/reusable packaging applications; the dynamic behavior of PE foam offers protection even after multiple drops with little deterioration of the material. Though a prototype design with recycled PE foam was not developed for this study, costs savings from packaging reuse are included here for completeness. Returnable/reusable packaging was discussed in the previous chapter, Environmental Evaluation, when various waste disposal options were presented.

Consumer Values

In the field of industrial products, packaging serves the functions of containment, protection in distribution, and identification. Most manufacturers consider the least cost package to be most appropriate, provided it performs adequately, regardless of what the competition is doing. The consumer goods field is considerably more complex. The functions of containment and protection are much like those for industrial packaging. Identification, however, must stress brand names and product features, and provide purchase appeal.[73] Consumers respond to their own perceptions of value; packaging designers must be aware of how consumers interpret packaging and package changes. Consumer values supporting the environment are apparent from the results of a number of public surveys.

"Consumers consider the 'garbage crisis' today's most important environmental issue and see ecologically sound packaging as a solution," according to a poll by a leading package-design firm."[74] In this survey, consumers put solid waste ahead of air pollution as an area of concern for the first time since 1989. Ninety-three percent of the consumers surveyed site buying products in environmentally sound packaging as a solution to the solid-waste issue.[75] However, in another survey conducted by the journal *Packaging*, consumer faith in package recyclability as a means of lessening the trash burden is decreasing.[76] Experts in the packaging field predict source reduction (using less packaging material) is the key to successful packaging.[77] Consumer preference for recyclable, refillable/reusable, and recycled packaging materials grew from 1993 figures; the growth in refillable/reusable packaging was the greatest at

23 percent between 1993 and 1994. From the same survey, consumers believe consumer electronic products and large household appliances use too much packaging. This opinion has continued to increase from 37.7 percent in 1991 to 52 percent in 1994.

These consumer opinions can support the application of any of the cushioning materials evaluated in this study if the materials are properly marketed. Many applications of EPS loose-fill product packaging are accompanied by a letter to the consumer describing the recycle and reuse programs available for used packaging. American Excelsior is establishing a similar informative letter with EcoPlank packaging.

CONCLUSIONS

The costs associated with packaging extend beyond those of material costs. The effectiveness of the packaging system, cubic efficiency, and consumer value can play important roles when identifying cost effective packaging. The material costs were quantitatively assessed in this study. When packaging the Philips' VCR, the prototype design for layered corrugated pads was the most cost competitive when compared to EPS, while the starch-based prototype design was nearly six times as much. MAYTAG's current packaging system, though inexpensive, results in a damage rate that may represent a cost inefficient system. The starch-based foam design, though expensive in comparison, may show positive performance (protective) characteristics. These differences are summarized in Table 15.

TABLE 15 - COMPARISON OF MATERIAL COSTS

Packaging System	Cost Per Packaging System	
	Philips' VCR	MAYTAG's Glass Panel
EPS	$0.40	NA
Bubble Wrap and Paper	NA	$0.65
Starch-Based Prototype	$2.35	$4.80
Layered Corrugated Prototype	$0.55	NA

NA: Not Applicable.

CHAPTER 7

CONCLUSIONS

This Cleaner Technology Demonstrations for 33/50 Chemicals project evaluated alternatives to EPS as a cushioning material in consumer and industrial packaging. EPS is an example of the priority use cluster "plastics and resins," and is produced from raw materials derived from the 33/50 chemical benzene. By demonstrating the technical, environmental, and economic characteristics of alternative materials, it is hoped that alternative materials will replace EPS in particular product packaging applications, thus reducing the emissions of benzene resulting from EPS production and use.

Three 'alternative' cushioning materials were identified for evaluation within this research; starch-based foam planks, layered corrugated pads, and recycled polyethylene foam. Though some have been used as cushioning in packaging applications in the past, these materials are termed 'alternative' because each offers unique features as well as adequate cushioning capabilities. These unique features include their manufacture from recycled materials, biodegradability, water solubility, recyclability, and reusability.

The goals of this project were to evaluate each packaging material in terms of performance (technical evaluation), environmental impact, and economic efficiency. The results of each evaluation are summarized below.

TECHNICAL EVALUATION

The results of the technical evaluation reveal the strengths and weaknesses of each protective packaging material. While the results of dynamic tests were utilized in prototype development, the applicability of static, stress-strain tests were not identified. Prototype demonstrations using starch-based foam and layered corrugated pads show the ability of these alternatives to replace EPS as a protective packaging material.

Under standard temperature and humidity conditions, dynamic drop test results (summarized in Table 16) revealed positive cushioning characteristics of each material. Using samples of 1.5 inches thick, layered corrugated pads offered as much protection as EPS for a single drop; starch-based foam and recycled PE foam displayed lesser protective characteristics. However, each displayed the ability to absorb multiple drops greater than that of EPS. High temperatures and extremes in humidity seem to have the most significant impact of starch-based foam, causing sample deterioration which resulted in decreased cushioning ability. Little change in dynamic cushioning properties were identified for EPS, layered corrugated pads, and recycled PE foam.

Test results from dynamic drops (i.e., cushioning curves) were used, in conjunction with design expertise, to develop effective prototype protective packaging designs. EPS, while adequately protecting a VCR from damage, did not perform to expected levels. Prototype designs using layered corrugated pads and starch-based foam also protected the VCR from damage, and performed to a level comparable to that of EPS. In applications which protect glass products, starch-based foam prototype designs also revealed positive protective properties. These results are presented in Table 17.

TABLE 16 - SUMMARY OF OPTIMAL STATIC LOADS AND CORRESPONDING G-FORCES FOR EACH MATERIAL		
Material	Optimal Static Load (lb/sq inch)	G-force
EPS	0.82	51
Recycled PE Foam	0.37	55
HD Starch-Based Plank	0.64	72
LD Layered Corrugated	0.52	46

Key: HD = High Density
LD = Low Density

Note: Drop Height = 30 inches; Sample Thickness = 1.5 inches

TABLE 17 - SUMMARY OF PROTOTYPE DESIGN RESULTS		
Packaging System	VCR Packaging	Glass Panel Packaging
EPS (current)	Passing	NA
Bubble Wrap and Paper (current)	NA	10% damage rate
Layered Corrugated Pads (prototype)	Passing	NA
Starch-Based Foam Plank (prototype)	Passing	Passing

NA: Not Applicable; a design using this material was not tested.

ENVIRONMENTAL EVALUATION

The purpose of the environmental evaluation was to assess the various and unique environmental loadings resulting from the life cycle of each packaging material, from raw material extraction to processing and waste disposal. A shift in environmental burdens would occur if an alternative packaging material was used to replace EPS in consumer product packaging applications. The environmental burdens for EPS would be reduced if another material was used, while the environmental burdens resulting from the manufacture of an alternative material would possibly increase due to increased demand. Table 18 summarizes the pollutants which result from the life cycle of EPS, starch-based foam plank, and layered corrugated pads. Due to the lack of a prototype design, limited data was available for recycled PE foam, and thus is omitted from this summary.

This study was implemented to show potential reductions in the use and release of the 33/50 chemical benzene resulting from the manufacture and use of EPS. The environmental loadings presented for pre-manufacturing show reductions of benzene releases are possible if EPS were replaced by an alternative material. Facility-specific information indicates that releases of pentane would decrease, while energy consumption has the potential to increase or decrease, depending on the alternative material selected. Waste disposal options available for each material show potential benefits and depend on the waste management option selected regardless of material.

TABLE 18 - SUMMARY OF ENVIRONMENTAL LOADINGS

Life-Cycle Stage	EPS	Starch-Based Foam Plank	Layered Corrugated Pads
Pre-Manufacturing	Benzene dominates all environmental releases to both air and water.	The use of agricultural chemicals results in the only pre-manufacturing release of 33/50 chemicals.	Few, if any 33/50 chemical releases are expected from this life-cycle stage.
Package Manufacture	Pentane emissions (VOC) dominate the environmental profile for this life-cycle stage.	Chemical releases to air and water are not expected from this life-cycle stage. Energy consumption is the most significant among materials tested.	Few emissions to water, and no emissions to air are expected within this life-cycle stage. Energy consumption is the lowest among materials tested.
Waste Management	Waste typically goes to landfill due to limited infrastructure which supports its recycle.	Dissolution with water may significantly impact wastewater treatment facilities. Composting represents another waste management option.	Material has the potential to be recycled using the existing residential recycling infrastructure.

The use of an alternative packaging material, however, will result in its own unique environmental burdens. For starch-based foam, the pre-manufacturing processes of agricultural chemical production, crop production, and corn processing must be considered. Though the release of benzene is not expected, other 33/50 chemicals may be emitted, primarily in agricultural chemical manufacturing processes. For example, for the production of atrazine, a pesticide commonly applied to corn, the 33/50 chemical hydrogen cyanide is used. The package manufacturing life-cycle stage consumes significantly more energy than the EPS package manufacturing process, and waste disposal options must consider the potential impact on wastewater treatment facilities if the starch-based packaging material was dissolved and washed down the drain.

The use of layered corrugated pads as a replacement for EPS also results in unique loadings to the environment. Pre-manufacturing data indicate few, if any 33/50 chemical emissions to air or water, however, other environmental loadings are expected. The manufacture of layered corrugated pads consumes the least energy of any packaging alternative, and is expected to result in no additional environmental loadings to air or water. Finally, the potential to recycle corrugated materials in existing infrastructures offers a benefit above EPS.

The comparison of environmental loadings did not consider the toxicity of the pollutants/contaminants, nor their persistence in the environment, potential exposure to humans, and impact on human health and the environment. The impacts of energy consumption, such as global warming, have not been addressed either. When considering the potential shift in environmental loadings between selected materials, these issues must also be considered. However, from the information presented in this evaluation, layered corrugated pads seem to represent a better packaging material on environmental merits.

ECONOMIC EVALUATION

The costs associated with packaging extend beyond those of material costs. The effectiveness of the packaging system, cubic efficiency, and consumer value can play important roles when identifying cost effective packaging. The material costs were quantitatively assessed in this study. When packaging the Philips' VCR, the prototype design for layered corrugated pads was the most cost competitive when compared to EPS, while the starch-based prototype design was nearly six times as much. MAYTAG's current packaging system, though inexpensive, results in a damage rate that may represent a cost inefficient system. The starch-based foam design, though expensive in comparison, may show positive performance (protective) characteristics. These differences are summarized in Table 19.

TABLE 19 - COMPARISON OF MATERIAL COSTS

Packaging System	Cost Per Packaging System	
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Layered Corrugated Prototype	$0.55	NA

NA: Not Applicable.

RECOMMENDATIONS

The results of this study show the potential application of alternative packaging materials to replace current uses of EPS. Potential environmental benefits and the economic competitiveness of selected materials offer further support for the use of these alternative materials. There is, however, more information that must be made available to packagers and manufacturers to support the use of the alternative materials. This information, identified as future research topics, includes the following:

- The technical evaluation assessed each material at a single thickness over a finite set of static loads. It is the opinion of this research team that further tests be conducted to more accurately define the dynamic cushioning curves over a wide range of material thicknesses.
- The creep tests completed in this study were terse and qualitative. To support the use of alternative materials, boundaries for the characteristics of creep (or set) must be established.
- A greater understanding of the effects environmental conditions (e.g., temperature and humidity) have on the materials and their performance capabilities is suggested.
- Finally, all packaging designers must divorce themselves from the practice of filling void space when packaging consumer products. The cushioning characteristics of the alternative materials must be properly utilized, and materials use must be optimized to offer a competitive price for the alternative materials.

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APPENDICES

APPENDIX A

TRIAXIAL PIEZORESISTIVE ACCELEROMETER

ENDEVCO® MODEL 7267A
TRIAXIAL PIEZORESISTIVE ACCELEROMETER
Replaceable Elements

The ENDEVCO Model 7267A is a replaceable-element triaxial accelerometer designed to measure acceleration in three mutually perpendicular axes. Although designed for installation in the heads of anthropomorphic test dummies used in automotive crash studies, it has application wherever triaxial accelerometers are used for steady state or long duration pulse measurements. The Model 7267A uses ENDEVCO's PIEZITE® piezoresistive elements in half-bridge configuration.

The three sensors are mutually perpendicular and are positioned so their sensitive axes pass through the centers of seismic mass and intersect at a single point.

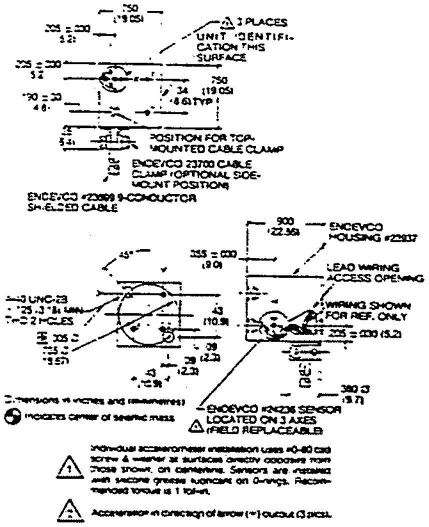
Each sensor is replaceable. It is held in place by a single screw for easy installation or removal by the user. Solder pins are provided for electrical connection of an easily replaced nine-conductor cable. Both side and top cable entry holes are provided. Accessories include a 10 ft (3.05 m) cable and a mounting base. Sensors, housing and cable clamp are available as replacement components.

(All values are typical at +75°F [+24°C] unless otherwise specified.)

		MODEL 7267A
PERFORMANCE		
RANGE	g	±1500
SENSITIVITY (at 10 Vdc excitation, ref 100 Hz)		
Typical/Minimum	mV/g	0.15/0.10
NON-LINEARITY & HYSTERESIS (% of reading, max, to full range)	%	±1 (±2% max at 1500 g)
FREQUENCY RESPONSE (±5% max, ref 100 Hz)	Hz	0 to 2000
MOUNTED RESONANT FREQ[1]	Hz	12 000 Hz
DAMPING RATIO		0.005
TRANSVERSE SENSITIVITY (max)	%	3
THERMAL SENSITIVITY SHIFT (ref +75°F [+24°C])	%	±3
	°F	−10/+150
	°C	−23/+66
ZERO MEASURAND OUTPUT (max)	mV	±25
THERMAL ZERO SHIFT (max)[2]	mV	±15
ELECTRICAL		
EXCITATION[3,4]	Vdc	10.0
INPUT RESISTANCE[3,5]	Ω	1000
INSULATION RESISTANCE (minimum at 100 Vdc)	MΩ	100, pin to case
GROUNDING		Cable shield common to case. Isolated from sensor pins
PHYSICAL		
WEIGHT (excluding cable)	oz (gm)	1.76 (50)
CASE MATERIAL		Corrosion-resistant steel
ELECTRICAL CONNECTIONS[6]		Integral nine-conductor shielded cable
MOUNTING/TORQUE		Two holes for 4-40 mounting screws. 6 lbf-in (0.68 Nm)
ENVIRONMENTAL		
ACCELERATION LIMITS (in any direction)		
Static	g	4000
Sinusoidal	g	1000, below 2000 Hz
Shock	g	4000 half-sine pulse, 500 μs or longer (Note 1)
TEMPERATURE		
Operating	°F (°C)	−10 to +150 (−23 to +66)
Non-Operating	°F (°C)	−100 to +300 (−73 to +149)
HUMIDITY		Individual Sensors hermetically sealed by welding and glass-to-metal fusion

CALIBRATION DATA SUPPLIED
(at 75°F [24°C] and 10.00 Vdc excitation)

SENSITIVITY (at 100 Hz)	mV/g
ZERO MEASURAND OUTPUT	mV
MAXIMUM TRANSVERSE SENSITIVITY	% of calibrated sensitivity
INPUT RESISTANCE	Ω



NOTES

[1]In shock measurements, minimum pulse duration for half sine or triangular pulses should exceed 0.5 milliseconds to avoid excessive high frequency ringing. (See Endevco Piezoresistive Accelerometer Manual.)

[2]Thermal Zero Shift millivolts specified are at −10°/+150°F (−23°/+66°C), reference +75°F (+24°C).

[3]Rated excitation is 10.0 Vdc. The strain gage elements have a positive temperature coefficient of resistance of approximately 0.5% per °F. Power supply current regulation capability should be carefully considered when operating at low temperature extremes, especially when exciting more than one transducer from a single supply.

[4]Other excitation voltages may be used to 15.0 Vdc, but should be specified at time of order to obtain a more accurate calibration. Warmup time to meet all specifications is two minutes, maximum. Endevco Model 4423 Signal Conditioner is recommended as the excitation source.

[5]Half-bridge input resistance measured across the excitation leads. It does not include external bridge completion resistance. Measurand at approximately 1 Vdc. Bridge resistance increases with applied voltage.

[6]Three-pin solder terminations on each of three recessed surfaces. Cable entry holes for either side or top cable entry.

[7]7267A meets SAEJ211 specifications for anthropomorphic dummy instrumentation.

ACCESSORIES INCLUDED

Model 23898 Mounting Base; Model 23700 Cable Clamp; Model 23699 Cable, 10 ft (3.05 m) long. Longer length available. Cable is factory-installed through top entry. Side entry on special order.

REPLACEMENT COMPONENTS

Model 24236 Sensor. (Includes installation hardware kit 24356.) Model 23937 Housing.

7.37 PS7267-A-A

Continued product improvement necessitates that Endevco reserve the right to modify these specifications without notice.
Endevco maintains a program of constant surveillance over all products to ensure a high level of reliability. This program includes attention to reliability factors during product design, the support of stringent Quality Control requirements, and compulsory corrective action procedures. These measures, together with conservative specifications have made the name Endevco synonymous with reliability.

APPENDIX B
STEP-BY-STEP PROCEDURES FOR LABORATORY TESTS

- **Dynamic Drop Tests**
- **Static Compression Tests**
- **Creep Tests**

The procedures followed in this study are presented step-by-step in Figures B1, B2, and B3. Further details, as defined by ASTM Standard Method D 1598 - 91, follow the figures.

FIGURE B1 - STEP-BY-STEP DYNAMIC DROP TEST PROCEDURE	
Calibration	
Periodically, transducers are returned to the manufacturer for re-calibration. The procedure described below is followed in the interim, and represents Philips' standard operating practices.	
Step #1	Secure two identical transducers together using double-sided adhesive tape;
2	Drop the transducer pair and record dynamic acceleration-time histories for each transducer; and
3	Compare each read-out; if peak G-force readings for each transducer are within 5 to 10 percent of each other, each transducer is considered calibrated.
Preparation of Apparatus	
Step #1	Mount desired load to static load platen;
2	With double-sided tape, mount transducer to the top surface of the static load platen;
3	Connect compressed air source to pneumatic suction platen; and
4	Set desired parameters within the Setup menu of the computerized data acquisition system.
Preparation of Sample	
Step #1	Measure and record the thickness of material samples (see details);
2	Measure and record the area of material samples (see details);
3	Measure and record the mass of material samples (see details); and
4	Mount a single material sample on apparatus platform with double-sided tape.
Dynamic Tests	
Step #1	Lower pneumatic suction platen onto static-load platen;
2	Open compressed air valve to initiate suction;
3	Using the winch, begin to raise platens to the desired drop height (see details);
4	Position platform, with mounted sample, under the static-load platen;
5	Using a tape measure, position static load such that the distance from the top of the sample material to the bottom of the mounted static load equals that of the desired drop height (see details);
6	Close compressed air value allowing the static-load platen to drop freely onto material sample;
7	Save resulting dynamic drop test curve as single, retrievable file;
8	Ready the computerized data acquisition system by clearing operating memory;
9	Repeat Dynamic Test Steps #1 through #9 to generate a series of five dynamic drop test curves for a single material sample; and
10	From single event drop test curves record peak G-force.

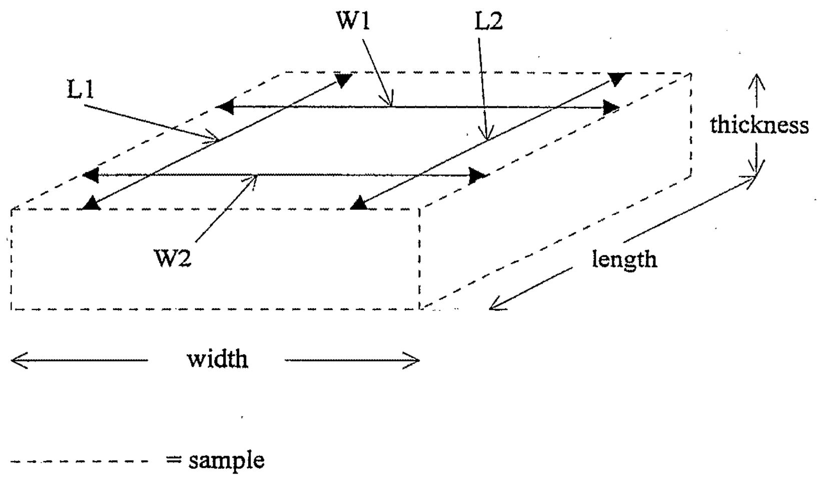
FIGURE B2 - STEP-BY-STEP STATIC STRESS-STRAIN TEST PROCEDURE
Preparation of Apparatus
Step # 1 Mount compression cell onto top crosshead of Instron;
2 Record gear configuration;
3 Mount and adjust paper chart and recording pen; and
4 Record chart speed and range.
Prepareation of Sample
Step # 1 Cut samples to desired size with razor blade;
2 Measure and record the thickness of material samples (see details);
3 Measure and record the area of material samples (see details); and
4 Mount a single material sample on platform of lower crosshead.
Dynamic Tests
Step #1 Engage Instron motor, raising lower crosshead until sample touches lower surface of compressometer, then disengage motor;
2 Turn on pen and chart switches;
3 Engage motor again, recording displacement and time parameters as the sample is compressed;
4 Disengage motor and turn off pen and chart switches when sample has been compressed to 50 percent original thickness; and
5 Transpose time-displacement data into stress-strain data.

FIGURE B3 - STEP-BY-STEP CREEP TEST PROCEDURE
Preparation of Apparatus
Step #1 Condition environmental chamber to 50 °C; and
2 Determine required weight and moment arm length to impose proper loads to each sample.
Preparation of Sample
Step #1 Measure and record the area of material samples (see details); and
2 Position samples under moment arms within environmental chamber.
Dynamic Tests
Step #1 Load moment arms with weight; and
2 Record the change in specimen thickness after one, two, five, ten, fifteen, and twenty minutes; record the change in specimen thickness after one, two, five, ten, and fifteen hours; record the change in specimen thickness after one, two, five, and seven days; for the remainder of the test measure the change of specimen thickness once per week.

<u>Details for Measuring Thickness</u>. A sample thickness of 1.5 inch was selected prior to test initiation, based on industry partner requirements. Material manufacturers were asked to submit cushioning material samples of this thickness. Following the ASTM methodology, on each test day the thickness of each material sample was measured and recorded. Using a calipers equipped with calibrations able to measure to the nearest thousands of an inch (0.001 in.), four measurements of thickness were recorded for each sample, one at each sample edge. The thickness of the sample is then reported as the average of these four measurements.

Details for Measuring Area. The area of each material samples was dictated by the apparatus used during test series. The sample platform and falling static load platen restricted a sample area during the dynamic drop tests to the dimensions of 6 x 6-inch square; 4 x 4-inch square samples were used during stress-strain tests, consistent with the area offered by the crosshead platform; sample sizes for the creep tests were 4 x 4-inch square for starch-based foam plank, 3 x 3-inch square for recycled polyethylene foam, and 3 x 4-inch rectangular of layered corrugated and EPS, each offering the appropriate load for the test. Samples from each material manufacturer were obtained in 6 x 6-inch square pieces; required sample sizes were cut from these samples using a razor blade. For each sample, a total of four measurements were recorded; two measurements for length and two measurements for width. Measurements were made to the nearest 1/32-inch using an engineering ruler. The area was then determined by averaging each pair of measurements and then multiplying the averages together, as expressed in Figure B4.

FIGURE B4 - SAMPLE SCHEMATIC AND AREA MEASUREMENTS



Area = (W1 + W2)/2 x (L1 + L2)/2

Details for Measuring Mass. The mass of each sample was measured and recorded using an Acculab battery-operated pocket scale (Pocket Pro™ 250-B). This scale is able to display mass in units of grams (as well as ounces and troy ounces), with a readability to the nearest tenth of a gram (0.1 g, or 0.01 oz, or 0.01 ozt.) and a maximum mass of 250 grams. The mass of each sample was measured and recorded in grams.

Additional information regarding test parameters and collected data include the following:

- The range of static loads for the dynamic drop tests was established by using a combination of stainless steel plates which offered six standard weights, from 8 to 33 pounds in 5-pound increments.
- Temperature and relative humidity of the storage room (an office at the Center for Clean Products) in which the samples were dept were measured and recorded daily during the series of dynamic drop tests.

- Static loads for the creep tests were set at five percent of the final strain established by the static stress-strain tests. This level of strain resulted in the following loads per area for each material: EPS, 8.7 lb/ sq in; starch-based foam, 0.3 lb/sq in; recycled PE foam, 2.2 lb/sq in; and layered corrugated pads, 4.3 lb/sq in.

APPENDIX C
EXAMPLE OF QUESTIONNAIRE TO ASSESS FACILITY-SPECIFIC ENVIRONMENTAL LOADING

ENVIRONMENTAL DATA QUESTIONNAIRE

The University of Tennessee Center for Clean Products and Clean Technologies is conducting research to evaluate the performance, cost, and environmental aspects of cushioning materials. Funded through a cooperative agreement with the U.S. Environmental Protection Agency, this project will evaluate the technical (i.e., performance), economic, and environmental aspects of the alternative cushioning materials in comparison to expanded polystyrene (EPS). Technical evaluations within the laboratory have been initiated for all cushioning materials. This questionnaire is intended to initiate the environmental evaluations by gathering needed data regarding environmental aspects of EPS foam manufacturing and materials use. With this questionnaire it is not the Center's intention to reveal proprietary information or trade secrets. The requested data, however, are required to evaluate all aspects of the process as it relates to the environment. Please respond to the following data requests as completely as possible.

Raw Materials

The information gathered in this section is intended to identify ALL materials incorporated into your standard EPS foam product. Please specify the following information regarding all materials that are used in its manufacture. This information will be used as the primary source of data for the assessment of life-cycle environmental aspects of all raw materials. Therefore, please be as specific as possible.

Polystyrene

resin/bead vendor/supplier ______________________________

resin/bead density as received ______________________________ (please specify units)

blowing agent (please specify) ______________________________

blowing agent/resin ratio (e.g., mass agent/mass resin) ______________________________

Does resin contain some recycle resin content? (check response) ☐ yes ☐ no

percent recycle content ______________ please specify units, by vol. OR by wt.)

source of recycled material ______________________________

Other Materials

Please identify any other materials used or incorporated into your standard EPS foams (e.g., mold release).

<u>Material</u> <u>Foam's Content (% by vol./wt.)</u>

____

____

____

Please attach applicable MSDSheets.

Energy Requirements

The energy requirements to manufacture EPS foam is also required to assess the total environmental impacts of the products under investigation. While manufacturing your foam products, what are the energy requirements for each process unit (or the entire manufacturing process as a whole)? If actual energy consumption figures are known, please offer that information in the following section; otherwise, complete the capacity, duty, and load information as presented (see note, below). For a comparison with other production processes and products under investigation, it would be ideal if this information would be presented on a per-unit-of-production basis. If this in not possible or practical, please present information on a single, common basis (e.g., average manufacturing day).

Energy Consumption of Entire Production System ____________________ (please specify units)

OR

Resin Delivery Unit:
  Actual Energy Consumption _________________________ (please specify units)
  OR
  Nameplate Capacity _____________________
  Duty _____________________
  Load _____________________

Steam Generator:
  Actual Energy Consumption _________________________ (please specify units)
  OR
  Nameplate Capacity _____________________
  Duty _____________________
  Load _____________________

Pollution Control Unit (please specify): _________________________________
  Actual Energy Consumption _________________________ (please specify units)
  OR
  Nameplate Capacity _____________________
  Duty _____________________
  Load _____________________

Other (please specify): _____________________________________
  Actual Energy Consumption _________________________ (please specify units)
  OR
  Nameplate Capacity _____________________
  Duty _____________________
  Load _____________________

Other (please specify): ______________________________

Actual Energy Consumption ____________________ (please specify units)

OR

Nameplate Capacity _________________

Duty _________________

Load _________________

Note: Duty is defined here as the percentage of time a process unit is operated; for example 6 hours out of an eight-hour day, or 75 percent duty. Load is defined here as the percentage of the unit's capacity which is being utilized; for example, a pump that has a nameplate capacity of 60 gal./min. but is operating at 45 gal./min. represents a load of 75 percent.

Waste Streams and Clean-Up

An assessment of the wastes generated during the manufacture of EPS foams will be accomplished utilizing the data gathered below. Please present generation rates for each of the waste streams identified below as average values based on overall production. For conversion and comparison with other products, the overall production rate is also requested.

Overall Production Rate __________________________________ (please specify units)

Do you generate non-hazardous wastes? ❑ yes ❑ no

If yes, please specify the following:

rate of generation ____________________________ (please specify units)

composition ________________________________

____

____

method of disposal ____________________________

What type(s) of recycling is being conducted within this manufacturing facility? Are the quantities of recycled materials included in the figure identified above for the non-hazardous waste stream? ____

____

____

Do you generate process wastewater? ❑ yes ❑ no

If yes, please specify the following:

average flow rate ____________________________ (please specify units)

average composition __________________________ (please specify units)

____

____

pretreatment ❑ yes ❑ no

If yes, please specify the following:

❑ required ❑ voluntary

describe treatment train ______________________________

____

____

Please attach pertinent permits.

Do you generate process air emissions? ❑ yes ❑ no

If yes, please specify the following:

❑ controlled ❑ uncontrolled

If controlled, please specify control technologies ______________________________

Please specify composition/constituents ______________________________

____

Please attach pertinent permits.

Do you generate hazardous wastes? ❑ yes ❑ no

If yes, please specify the following:

rate of generation ______________________________ (please specify units)

composition ______________________________

____

____

disposal method ______________________________

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