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Today's consumers are faced with a number of challenges from the moment they enter the grocery store. The thousands of packages are designed not only to attract and sell the products but to maintain the highest quality. Food and beverage packaging make up more than \$70 billion of the United States packaging market and more than \$200 billion worldwide (Wilkinson 1998). Paper and board packaging is the most common material and generally considered the most susceptible to insect attack. The widespread use of these susceptible packaging materials for food products is important because losses from insect infestation of packaged foods are the sum cost of growing, harvesting, transportation, processing, and packaging (Mullen and Mowery, 2000). When developing a package for a food product, several factors must be considered. The type of package (rigid or flexible), ability of the package to maintain food quality, cost, and availability of materials, and consumer acceptance are essential. An often overlooked problem is the ability of the package to be resealed.

Because of the abundant supply of similar products, attractive packaging that catches the consumer's eye and ensures a high quality product is essential. Excessive packaging can result in needless expense, while cheap packaging can lead to infestation by insects, microorganisms, and reduce the quality of the product. Packaging manufacturers are now moving toward green, or environmentally conscious, packaging while still protecting the food from the manufacturer to the consumer (Connolly 2011a). Product safety concerns include tamper-resistance and environmental issues raised in the manufacture

and disposal of the materials. Replacing the paperboard carton with a film-overwrapped tray will reduce the use of paperboard by 150 tons (Connolly, 2011a). Customer convenience is also important. It does little good to use a can that is difficult to open when a simple plastic pouch with a zipper seal will do (Kindle 2001).

Any comprehensive study of insect control in the food industry must consider the elimination or prevention of insect infestation. Most foods are presented to the consumer in packaging that is exposed to infestation from the point of manufacturer until it is consumed. Packaging must not only protect the product but also be attractive to the consumer. The finished product has added value because it is the sum of growing, harvesting, processing, storage, and transporting it to the consumer. In the 1950s and 1960s pesticides were used to protect against infestation. Then came the discovery that pesticides can migrate through paper and paperboard. Over the past few decades it has become clear that the use of toxic chemicals on consumer packaging is no longer a viable option.

Many consumers have experienced opening a box of crackers or a bag of flour to discover a thriving colony of Indianmeal moths, flour beetles, or other insects. Even worse is the feeling of eating a bowl of breakfast cereal and finding small wriggling insects floating in the milk. Although the food processor may take all possible precautions to package an insect-free commodity, they often have no control over the product during shipping and storage. Consumers are especially sensitive to these problems,

and manufacturers are concerned with providing the consumer with high quality products that meet their needs. Consumers usually hold the manufacturer responsible for the insect infestation, regardless of where or how the package became infested (Highland 1984). Manufacturers know that if the consumer finds an insect in a cereal package, it can make a lasting and often irreversible impression, and can result in the loss of a customer. A pet food manufacturer recently reported \$1 million in losses in one year in one product line because of insect infestation.

Many companies have implemented package-testing programs to improve resistance of packages to insect attack (Mullen and Mowery 2000). Insect-resistant packaging is the most common way to prevent insect infestation without using insecticides or repellents (Mullen and Highland 1988). Insect infestation is often the result of transportation-related problems, or prolonged storage under less than optimal conditions in the warehouse or on a grocer's shelf.

Since 1990 insect-related losses in pet food have declined with the use of insect-resistant packaging. Packages are designed to protect food products from the manufacturer to the consumer, a process that can span several years. Unfortunately, there is no perfect package that will provide the protection needed for all products under all conditions. Packages are usually tailored to fit the product being protected. The value of the product, length of time it must be protected, the economics of delivering a high quality product to the consumer, and other factors must be considered when designing and developing insect-resistant packaging.

Biology of Stored-Product Insects

Most stored-product insect pests are cosmopolitan. They have become established across the world over the years by way of international trade (Highland 1977). To survive, many species of stored-product insects infest packaged foods where they have an ample supply of nourishment for offspring and where they are protected from chemicals that may be used to kill them. Because of distribution practices, contaminated products can often be moved from one geographical location to another. In local warehouses and retail stores, infestations can spread from package to package. While food products can become

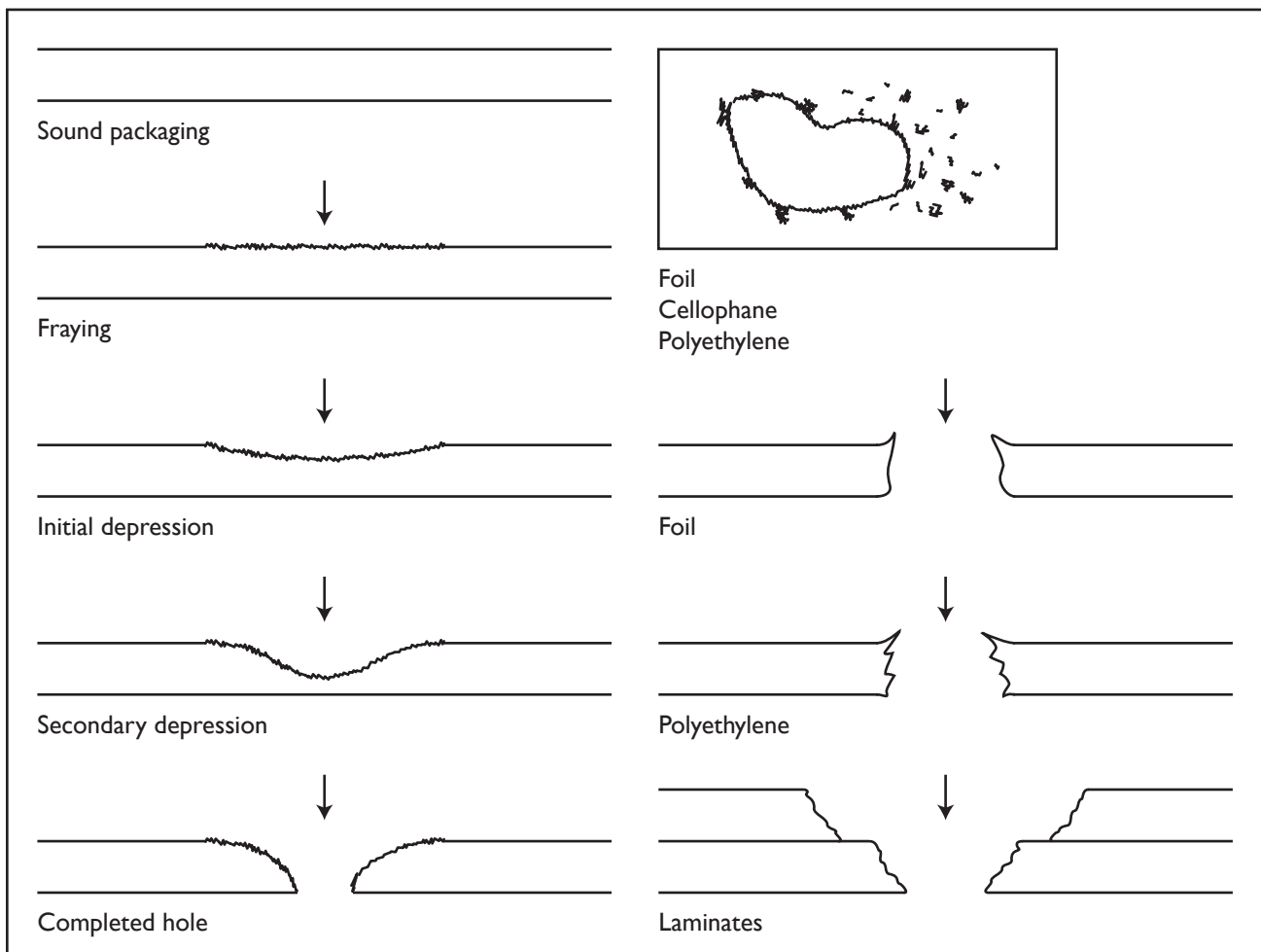
infested at any point in the marketing channel, they are most likely to become infested during extended storage periods. Some products are more susceptible to insect infestation than others. These products can serve as insect reservoirs, leading to the infestation of other products (Highland 1984). Dry pet foods and birdseed are often sources of infestation. Most pet foods are packed in multiwall paper bags that are generally not very insect resistant because they lack adequate seals and closures. Food may also become infested during shipment in trucks, railcars, and ships, as well as during retail storage, or even in the home.

How Insects Enter Packages

To begin a discussion of insect-resistant packaging, it is important to understand the insect pests that most commonly attack packaged foods. Highland (1984, 1991) separated package pests into two categories, penetrators and invaders (Table 1). Invaders are insects that typically have weakly developed mouthparts at both the larval and adult stages (Wohlgemuth 1979). The invaders account for more than 75% of the infestations (Collins 1963). Invaders commonly enter packages through openings resulting from mechanical damage, defective seals, or holes made by other insects penetrating the package (Mullen and Highland 1988). The newly hatched larvae of invaders typically cause the most damage because they are able to fit through holes as small as 0.1 mm wide (Wohlgemuth 1979). Typical insect penetration into food packaging materials is shown in Brickley et al. (1973) and illustrated in Figure 1. Most infestations are the result of invasion through seams and closures, and rarely through penetrations (Mullen 1997). For example, the adult sawtoothed grain beetle has been shown to enter packaging through openings less than 1 mm in diameter, and the adult red flour beetle can enter holes in packaging that are less than 1.35 mm in diameter (Cline and Highland 1981). Many insects prefer to lay eggs in tight spaces, such as those formed when multiwall paper bags or paperboard cartons are folded to create closures. These refuges provide a safe place to lay eggs and also give the newly hatched larvae an ideal location to invade the packages.

Table 1. Classification of pests that commonly infest packaged food¹.

Penetrators	Invaders
Red Flour Beetle (<i>Tribolium castaneum</i>)	Red flour beetle (<i>T. castaneum</i> .)
Confused Flour Beetle (<i>T. confusum</i>)	Confused flour beetle (<i>T. confusum</i>)
Warehouse beetle (<i>Trogoderma glabrum</i>)	Merchant grain beetle (<i>Oryzaephilus mercator</i>)
Rice weevil (<i>Sitophilus oryzae</i>)	Sawtoothed Grain Beetle (<i>O. surinamensis</i>)
Almond moth larvae (<i>Cadra cautella</i>)	Almond moth larvae (<i>C. cautella</i>)
Indian meal moth larvae (<i>Plodia interpunctella</i>)	Indianmeal moth larvae (<i>P. interpunctella</i>)
Lesser grain borer (<i>Rhyzopertha dominica</i>)	Squarenecked grain beetle (<i>Cathartus quadricollis</i>)
Cadelle (<i>Tenebrodes mauritanicus</i>)	Flat grain beetle (<i>Cryptolestes pusillus</i>)
Drugstore beetle (<i>Stegobium paniceum</i>)	Rice moth larvae (<i>Corcyra cephalonica</i>)

¹ Adapted from Highland 1984**Figure 1.** Direction of insect penetration into food packaging adapted from Brickey et al. 1973.

Penetrators

Insects classified as penetrators are those that can chew holes directly into packaging materials. Penetrators are most dangerous at the larval stage, though some beetle species can also be dangerous as adults

(Wohlgemuth 1979). Insects such as the lesser grain borer, *Rhyzopertha dominica* (Fab.); the cigarette beetle, *Lasioderma serricorne* (Fab.); the warehouse beetle, *Trogoderma variabile* Ballion; the rice weevil, *Sitophilus oryzae* (L.); the cadelle, *Tenebroides*

mauritanicus (Linnaeus); and the larvae of the rice moth, *Corcyra cephalonica* (Stainton), are known to be good package penetrators and are capable of boring through one or more layers of flexible packaging materials. The larvae of the Indianmeal moth, *Plodia interpunctella* (Hübner), under some conditions are also good penetrators and may be the most serious pests of packaged foods (Mullen and Highland 1988, Mueller 1998). The warehouse beetle, classified as a penetrator, is more specialized in the food products it infests and is often found in packages of dry pet food and dry pastas. It can create an additional problem to the consumer because the cast skins of the larvae can cause allergic reactions. The drugstore beetle, *Stegobium paneceum* (L.), is a strong penetrator and infests a wide variety of foods (Highland 1991).

Invaders

Other species are classified as invaders and enter packages through existing openings. Some common invaders include the sawtoothed grain beetle, *Oryzaephilus surinamensis* (Linnaeus); the red flour beetle, *Tribolium castaneum* (Herbst); the confused flour beetle, *T. confusum* Jacquelin du Val; and the flat grain beetle, *Cryptolestes pusillus* (Schoenherr) (Mullen and Highland 1988). The most important invaders are the larvae of the genus *Tribolium* (flour beetles), the genus *Oryzaephilus* (grain beetles) and freshly hatched moth larvae (Wohlgemuth 1979).

The above classifications of invaders and penetrators are regularly used to describe packaging pests, but these classifications are actually artificial, because some invaders can become penetrators in certain circumstances, and vice-versa. Under some circumstances, larvae of the Indianmeal moth and the almond moth penetrate packages. The larvae are generally classified as invaders, although in certain circumstances, they can be penetrators as well (Mullen and Mowery 2000). Both penetrators and invaders will exploit package flaws or other existing openings in order to reach a food product, and some invaders can chew directly into weak packaging materials such as paper and cellophane.

Considering that insect infestation of stored consumer food products is of such importance to the industry, disproportionately little has been done to describe the behavior and mechanisms by which insects invade packaged goods. Although it is generally thought invaders enter packages through

existing openings, little information is available to support this belief.

Mechanism of Entry

Aside from adult stored-product moths, which do not feed, most stored-product insect adults and larvae feed in order to sustain themselves. When faced with consumer food packages both invaders and penetrators will take advantage of any sort of opening in a packaging material in order to gain entry. These openings may form as a result of the chewing of penetrators, as rips, tears, or as punctures resulting from normal wear and tear throughout the handling process. Openings in packaging may also be made deliberately by the manufacturer in the form of “vents” which allow pressure equalization. This way, the manufacturer can avoid the bursting or shrinking of food packages during shipment over changing altitudes and temperatures.

In most cases, insect pests enter packages through existing openings that are created from poor seals, openings made by other insects, or mechanical damage. Most infestations are the result of invasion through seams and closures, and rarely through penetrations (Mullen 1997). Many insects prefer to lay eggs in tight spaces, such as those formed when multiwall paper bags or paperboard cartons are folded to create closures. These refuges provide a safe place to lay eggs and also give the newly hatched larvae an ideal location to invade the packages.

Odor Escape Through Openings

Olfaction is the means by which stored-product insects identify packaged consumer food products as a location in which to carry out important life functions such as finding food, mate finding, and oviposition. When an insect “smells” food, it will try to reach it. The vent holes made to reduce bursting also allow odors to escape and often provide insect pests an access point for entry. Stored-product insect larvae are very small and are able to enter packages through the smallest of openings (Barrer and Jay 1980) and can enlarge these opening to gain access. Barrer and Jay (1980) determined that the odor of kibbled wheat, when diffused into a 10m³ cage through 10-1 mm diameter holes, strongly attracted gravid free-flying *Ephestia cautella* (Walker) females

that were seeking ovipositing sites. When *E. cauttella* females cannot gain direct access to the grain, it is believed they will oviposit in the immediate vicinity of the opening through which the food odor is escaping, possibly to allow some larvae access to the grain upon hatching (Barrer and Jay 1980). Mated female sawtoothed grain beetles have been shown to have a more rapid response to the odor of carob distillate than virgin females (White 1989). It has been speculated that mated sawtoothed grain beetle females respond more rapidly to food odor due to the greater effort expended in egg production (White 1989).

Insect age also has an effect on response to food odor. White (1989) determined that two-day-old sawtoothed grain beetles showed a significant preference for the odor of carob distillate, and the response increased with adult age up to 16 to 20 days old. Honda *et al* (1969) showed that newly emerged *Sitophilus zeamais* Motschulsky less than 10 days old are more sensitive to attractants from rice than older weevils.

Package Design

Most non-perishable food items are shipped in consumer-sized packages and most of these, with the exception of canned food, are susceptible to insect attack (Mullen 1994). Seals and closures often can be improved by changing glue patterns or the type of glue used. Generally a glue pattern that forms a complete seal with no channels for the insect to crawl through is the most insect resistant. Sharp folds and buckles should be avoided because they weaken the material and provide easier access by pest insects (Wohlgemuth 1979). Insect resistance can also be improved by overwrapping the packages with materials such as oriented polypropylene films (Mullen and Mowery 2000). When subjecting snack bars to infestation by larval Indianmeal moths, the bars with perfect shrink wraps remained uninfested for 28 days when compared to those with flaws in the shrink wrap (Davis and Pettitt 2002).

To maximize the effectiveness of overwraps, they should fit tightly around the package. If overwraps are not completely sealed, insects often can gain entry at the corners of folded flaps. If the overwrap is sealed tightly, the movement of insects will be restricted, reducing the chances of infestation. Although it is impossible to avoid vulnerable spots,

it is important to be aware of the problems they can cause.

Another means of discouraging insect infestation is through the use of odor barriers (Mullen 1994). Food odors may be prevented from escaping the package through the use of barrier materials, resulting in a package that is “invisible” to invading insects. Flexible packaging with acrylic, PVdC (polyvinylidene chloride), or EVOH (ethylene vinyl alcohol) can improve odor retention (Sacharow and Brody 1987). These materials have been used with some success. Any flaw in the package will negate the odor-proof qualities of the package (Mullen and Highland 1988). Studies reported by Mullen (1997) showed that when odor barriers were used to protect a commodity, only those packages with flaws became infested.

Packaging Materials

Food products are packaged in a wide variety of paper and plastic materials. New materials are constantly being added to the list and are too numerous to discuss in detail. Paper is still one of the most widely used products and is certainly one of the most easily penetrated materials. Paper is often used with foil and polyethylene to form multiwall packages. This type of packaging is often found in pet food bags. Paper offers little resistance to insect penetration although it provides excellent strength, serves as a moisture barrier, and can be grease proof. Bags with a heat-sealable inner layer can be sealed, but the outer plies must be folded and glued. The sealed end flaps of these packages provide insects with a protected area in which eggs can be deposited. When the young larvae emerge, they often have little trouble entering the package through existing openings that occur in commercially sealed packages. These minute openings, which exist in most flexible packaging, allow odors to escape that will attract pests. Often they are sufficiently large to permit entry of the first instar larvae of most stored-product insects. A well-sealed airtight package can create additional problems. Changes in air pressure or temperature can create a swelling or shrinking of the package (Wohlgemuth 1979). This is often avoided by inserting small ventilation holes to allow the pressure to equalize. These vent holes behave as an imperfect seal and often can provide access for invading insects. This effect can be avoided by creating a tortuous path for the insects to follow. One of

the simplest methods to create a tortuous path is the use of a double heat seal created so there are vents at opposite ends of each seal. This method has been shown to allow for pressure equalization while limiting insect infestation.

Cellophane is one of the oldest plastic films to be commercialized. The desirable physical characteristics of cellophane include transparency, clarity, and heat sealability. Many of these attributes were lacking until nitrocellulose was developed in 1927 (Sacharow and Brody 1987). Studies on cellophane-wrapped packages conducted at the USDA Grain Marketing and Production Research Center in Manhattan, Kan., have shown that both dry cat food and raisins packaged in cellophane were very susceptible to penetration by a variety of stored-product insects including the Indianmeal moth, *P. interpunctella*, the warehouse beetle, *T. variable*, and the cigarette beetle, *L. serricornis*.

Paper and cellophane are probably the least resistant to insect penetration of the flexible packaging materials in use today. Depending on environmental conditions, some insect species can penetrate kraft paper in less than one day (Highland 1984). Adding multi-ply construction adds little to the resistance.

A recent study comparing standard commercial multiwall paper bags, reverse printed multiwall, and woven poly reverse printed bags to increase resistance to infestation to the Indianmeal moth illustrates the need for more extensive research to develop improved packaging (Vardeman unpublished), as illustrated in Table 2.

Table 2. Percentage of bags infested with respect to each type and the average number of Indianmeal moths (IMM) found within each bag.

Packaging	% Bags Infested	Avg No. IMM/ Bag
Standard multiwall (MW)	30	2
Reverse printed multiwall (RPP)	80	4
Woven-poly reverse printed (WPP)	90	12

Polyester (PET), first developed in 1941, has good resistance to insect penetration, but its use in packaging has been limited because of higher cost, less coverage per pound of material, and limited shrink properties (Sacharow and Griffin 1973). In recent years there has been a dramatic increase in the use

of PET and metalized PET in flexible packaging (Highland 1978). Polyvinylidene chloride (PVDC), a good odor barrier, when used alone, is a poor barrier to insects; however, laminates containing polyester and saran provide very good protection against insect penetration when the polyester side was exposed to insects (Rao et al 1972). Use of this material in packaging today is in refrigerated or frozen applications.

Flexible polymer films used in packaging can be penetrated by one or more species of insects. MRE (meals ready to eat) military rations, are packaged in 10-mil polyethylene and are generally resistant to penetration, but under extremely crowded conditions red flour beetle adults have been known to penetrate these packages. Even laminates can be susceptible to insect attack. Plastic has several advantages over paper for packaging. For example, it can ensure that the contained materials will remain in their original condition. Plastic packages can be colorful, attractive, and made into different sizes and shapes. Work done at the USDA in Manhattan, Kan., has shown that many plastic materials resist infestation by most stored-product pests. Recently, stand-up plastic pouches have become popular. The pouches have been shown to be very resistant to insect penetration. Zippered stand-up pouches made from a polyester/foil/nylon/polypropylene laminate offer an extremely strong and lightweight package, (Connolly 2011b) and excellent insect resistance. Earlier studies by Cline (1978) showed that insect survival in airtight plastic pouches was reduced and that no insects survived in unpenetrated packages after 12 weeks. VanRyckeghem (2011) listed several commonly used packaging materials and their resistance to penetration by insects (Table 3).

Repellents

Repellents, as the word implies, have the characteristics of repelling insect entry or movement across a treated surface. The use of repellent coatings on packages to prevent insect infestation is an area in which additional research needs to be conducted. In 1978 Highland listed the development of repellent treatments as a priority.

Through the years many repellent formulations have been tried with little if any success. Studies conducted by the senior author included natural and synthetic compounds. These compounds included Neem oil, methyl salicylate, DEET derivatives, and

Table 3. Resistance of common packaging materials to penetration by insects.

Complete resistance	Vacuum sealed jars and cans
Insect proof	Polycarbonate, polyethylene terephthalate (PET), polyester nylon plastics
Insect resistant	Cellulose acetate; polyamide; polyethylene (250 microns to 10 mils); polypropylene; Polyvinyl chloride
Susceptible	Acrylonitrile; polyactic acid (biodegradable plastic); polyethylene (125 microns)
No resistance	Ethylene vinyl acetate; kraft paper; corrugated paperboard; paper/foil/polyethylene; polyethylene (25 to 100 microns = 1 to 4 mils); polyvinylidene chloride (Saran)

insect growth regulators. Many of these compounds were effective in laboratory choice tests. Food odors from the packages either greatly reduced or completely eliminated the effectiveness of the repellent treatment. Another problem is the migration of the repellent compound through the packaging material. Recently, methyl salicylate (Repellcoat™) was patented (Radwan and Allin 1997) and received approval by both the EPA and FDA as a package treatment. This was particularly significant because it represents the first such approval and should make it easier for other materials to be approved. In 2009 the EPA approved ProvisionGard™, which uses the IGR methoprene and is now being considered for use in many package applications. ProvisionGard™ has been shown to be effective in reducing the entry of Indianmeal moth into bulk shipping packaging by 99.5%.

Summary

Packaged foods face many challenges before they are finally consumed. These include package flaws during manufacture, improper handling during shipment, inadequate storage conditions, lack of proper product rotation, and improper sealing in the home. Increased restrictions on pesticide use and emphasis placed on sanitation may be somewhat hindered by demanding production schedules, so the development of insect-resistant packaging is of increasing importance to both the consumer and the manufacturer. The consumer is assured of insect-free food, and the manufacturer is protected against loss of goodwill and lawsuits arising from insect infestations in consumer-sized packaging. Future research in this area will lead to the development of more effective packaging methods to ensure that packaged foods remain insect-free until consumed.

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