RESIDUE REVIEWS

Reviews of Environmental Contamination and Toxicology

Editor
FRANCIS A. GUNTHER

JANE DAVIES GUNTHER

ADVISORY BOARD

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Foreword

Worldwide concern in scientific, industrial, and governmental communities over traces of toxic chemicals in foodstuffs and in both abiotic and biotic environments has justified the present triumvirate of specialized publications in this field: comprehensive reviews, rapidly published progress reports, and archival documentations. These three publications are integrated and scheduled to provide in international communication the coherency essential for nonduplicative and current progress in a field as dynamic and complex as environmental contamination and toxicology. Until now there has been no journal or other publication series reserved exclusively for the diversified literature on "toxic" chemicals in our foods, our feeds, our geographical surroundings, our domestic animals, our wildlife, and ourselves. Around the world immense efforts and many talents have been mobilized to technical and other evaluations of natures, locales, magnitudes, fates, and toxicology of the persisting residues of these chemicals loosed upon the world. Among the sequelae of this broad new emphasis has been an inescapable need for an articulated set of authoritative publications where one could expect to find the latest important world literature produced by this emerging area of science together with documentation of pertinent ancillary legislation.

The research director and the legislative or administrative advisor do not have the time even to scan the large number of technical publications that might contain articles important to current responsibility; these individuals need the background provided by detailed reviews plus an assured awareness of newly developing information, all with minimum time for literature searching. Similarly, the scientist assigned or attracted to a new problem has the requirements of gleaning all literature pertinent to his task, publishing quickly new developments or important new experimental details to inform others of findings that might alter their own efforts, and eventually publishing all his supporting data and conclusions for archival purposes.

The end result of this concern over these chores and responsibilities and with uniform, encompassing, and timely publication outlets in the field of environmental contamination and toxicology is the Springer-Verlag (Heidelberg and New York) triumvirate:

Residue Reviews (vol. 1 in 1962) for basically detailed review articles concerned with any aspects of residues of pesticides and other chemical contaminants in the total environment, including toxicological considerations and consequences.

Bulletin of Environmental Contamination and Toxicology (vol. 1 in 1966) for rapid publication of short reports of significant advances and discoveries in the fields of air, soil, water, and food contamination and pollution as well as methodology and other disciplines concerned with the introduction, presence, and effects of toxicants in the total environment.

Archives of Environmental Contamination and Toxicology (vol. 1 in 1973) for important complete articles emphasizing and describing original experimental or theoretical research work pertaining to the scientific aspects of chemical contaminants in the environment.

Manuscripts for *Residue Reviews* and the *Archives* are in identical formats and are subject to review, by workers in the field, for adequacy and value; manuscripts for the *Bulletin* are also reviewed but are published by photo-offset to provide the latest results without delay. The individual editors of these three publications comprise the Joint Coordinating Board of Editors with referral within the Board of manuscripts submitted to one publication but deemed by major emphasis or length more suitable for one of the others.

Coordinating Board of Editors

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Preface

That residues of pesticide and other contaminants in the total environment are of concern to everyone everywhere is attested by the reception accorded previous volumes of "Residue Reviews" and by the gratifying enthusiasm, sincerity, and efforts shown by all the individuals from whom manuscripts have been solicited. Despite much propaganda to the contrary, there can never be any serious question that pest-control chemicals and food-additive chemicals are essential to adequate food production, manufacture, marketing, and storage, yet without continuing surveillance and intelligent control some of those that persist in our foodstuffs could at times conceivably endanger the public health. Ensuring safety-in-use of these many chemicals is a dynamic challenge, for established ones are continually being displaced by newly developed ones more acceptable to food technologists, pharmacologists, toxicologists, and changing pest-control requirements in progressive food-producing economies.

These matters are of genuine concern to increasing numbers of governmental agencies and legislative bodies around the world, for some of these chemicals have resulted in a few mishaps from improper use. Adequate safety-in-use evaluations of any of these chemicals persisting into our foodstuffs are not simple matters, and they incorporate the considered judgments of many individuals highly trained in a variety of complex biological, chemical, food technological, medical, pharmacological, and toxicological disciplines.

It is hoped that "Residue Reviews" will continue to serve as an integrating factor both in focusing attention upon those many residue matters requiring further attention and in collating for variously trained readers present knowledge in specific important areas of residue and related endeavors involved with other chemical contaminants in the total environment. The contents of this and previous volumes of "Residue Reviews" illustrate these objectives. Since manuscripts are published in the order in which they are received in final form, it may seem that some important aspects of residue analytical chemistry, biochemistry, human and animal medicine, legislation, pharmacology, physiology, regulation, and toxicology are being neglected; to the contrary, these apparent omissions are recognized, and some pertinent manuscripts are in preparation. However, the field is so large and the interests in it are so varied that the editors and the Advisory Board earnestly solicit suggestions of topics and authors to help make this international book-series even more useful and informative.

"Residue Reviews" attempts to provide concise, critical reviews of timely advances, philosophy, and significant areas of accomplished or needed endeavor in the total field of residues of these and other foreign chemicals in any segment of the environment, as well as toxicological implications. These reviews are either general or specific, but properly they may lie in the domains of analytical chemistry and its methodology, biochemistry, human and animal medicine, legislation, pharmacology, physiology, regulation, and toxicology; certain affairs in the realm of food technology concerned specifically with pesticide and other food-additive problems are also appropriate subject matter. The justification for the preparation of any review for this book-series is that it deals with some aspect of the many real problems arising from the presence of any "foreign" chemicals in our surroundings. Thus, manuscripts may encompass those matters, in any country, which are involved in allowing pesticide and other plant-protecting chemicals to be used safely in producing, storing, and shipping crops. Added plant or animal pest-control chemicals or their metabolites that may persist into meat and other edible animal products (milk and milk products, eggs, etc.) are also residues and are within this scope. The so-called food additives (substances deliberately added to foods for flavor, odor, appearance, etc., as well as those inadvertently added during manufacture, packaging, distribution, storage, etc.) are also considered suitable review material. In addition, contaminant chemicals in any manner to air, water, soil or plant or animal life are within this purview and these objectives.

Manuscripts are normally contributed by invitation but suggested topics are welcome. Preliminary communication with the editors is necessary before volunteered reviews are submitted in manuscript form.

Department of Entomology F.A.G.
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February 15, 1985

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Moth control in stored grain and the role of *Bacillus thuringiensis*: An overview

By

BH. SUBRAMANYAM* and L. K. CUTKOMP*,**

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I. Introduction[1]

a) Moth pests infesting stored grain and their importance

Insects, among other biological agents like fungi, bacteria, and rodents, attack stored grains leading to losses in quantity and quality. On a worldwide basis 13

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[1]Insecticides mentioned in text are listed in Table VII.

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million tons of stored food grains are lost annually to insect depradations (Hall 1970). In the United States a USDA report (Anon. 1981) estimated annual storage losses of corn, wheat, barley, sorghum, and oats due to insects during 1950-1960 to be about 324.50 million bushels; the annual monetary loss during the same period being approximately $454 million. Therefore, reduction of loss and deterioration of stored grains by insects is necessary for maximum utilization of the food commodity.

Insects of economic importance in storage ecosystems predominantly belong to two major orders—Coleoptera (beetles) and Lepidoptera (moths). In terms of damage done, beetles are primary invaders because most feed both during their larval and adult life. Moths feed only as larvae. This review is limited to moth pests of stored grain since the major emphasis is on the use of *Bacillus thuringiensis*, which is pathogenic specifically to the Lepidopterous larvae (see section VI a). The term "stored grain" used in this discussion refers to cereal grains, legumes, and oilseeds.

Numerous moth species infest stored grain and a listing is presented in Table I. A survey in 61 countries of the world indicated the Angoumois grain moth (*Sitotroga cerealella*), almond moth (*Ephestia cautella*), Mediterranean flour moth (*E. kuehniella*), Indianmeal moth (*Plodia interpunctella*), and rice moth (*Corcyra cephalonica*) as the commonly occurring species on wheat, barley, millet, paddy, sorghum, rice, and maize. On an arbitrary scale based on occurrence in 19% of the cases, the listed moth pests were considered as major, and in 39 and 42% of the cases were classified as moderate and minor, respectively (Champ and Dyte 1977).

Details on the biology of the common species are available in Anon. (1980), Cotton and Wilbur (1974), Wilbur and Mills (1978), Woodroffe (1951 a and b), and Busvine (1980); and a summary of their ecology with references are listed in Howe (1965).

The larvae of most of the moths (e.g. *Ephestia spp.*, *P. farinalis*, *P. interpunctella*, *C. cephalonica*, and *N. granella*) feed within a group of grain kernels webbed together. Severe infestations, especially on the surface of the grain result in a mat of silken webbing caused by mature wandering larvae. An exception to the above mode of feeding is by larvae of *S. cerealella* which complete development inside grain kernels (Mills and Wilbur 1967). The false clothes moth, *H. pseudospretella*, is an omnivorous scavenger in cereal spillage and occasionally becomes a serious pest of bulk wheat and bagged flour (Woodroffe 1951 a). The whiteshouldered house moth occurs in association with the false clothes moth, but prefers peas and beans (Woodroffe 1951 b); it attacks stored cereal grains (Corbet and Tams 1943), bulk wheat (Richards and Waloff 1947), barley and corn (Strong and Okumura 1958). The meal snout moth, *P. farinalis*, is capable of attacking sound wheat of high moisture content (Madrid and Sinha 1982) but prefers grain that is damp and in poor condition (Anon. 1980). The Tineid, *T. bisselliella*, is an occasional but not serious pest in storage (Swenk 1922). In situations where the moisture content of the ears in the field is favorable for insect

Table I. *Lepidopterous insects recorded attacking stored grain*

Scientific name	Common name	Family	Reference
Corcyra cephalonica (Stainton)	Rice moth	Pyralidae	Anon. (1980)
Endrosis sarcitrella (Linnaeus) (=*E. lactella* (Schiff.))	Whiteshouldered house moth	Oecophoridae	Corbet and Tams (1943)
Ephestia (=*Cadra*) *cautella* (Walker)	Almond moth	Pyralidae	Anon. (1980)
E. elutella (Hübner)	Tobacco moth	Pyralidae	Anon. (1980)
E. (=*Cadra*) *figulilella* (Gregson)	Raison moth	Pyralidae	Anon. (1980)
E. (=*Anagasta*) *kuehniella* (Zeller)	Mediterranean flour moth	Pyralidae	Anon. (1980)
Haplotinea ditella (Pierce and Metcalfe)	Tineid moth	Tineidae	Zagulyaev (1967)
H. insectella (Fabricius)	Tineid moth	Tineidae	Zagulyaev (1967)
Hofmannophila (=*Borkausenia*) *pseudospretella* (Stainton)	Brown house moth or False clothes moth	Oecophoridae	Woodroffe (1951 a)
Nemopogon cloacellus (Haw.)	Tineid moth	Tineidae	Zagulyaev (1967)
N. granella (Linnaeus)	European grain moth	Tineidae	Zagulyaev (1967)
Plodia interpunctella (Hübner)	Indianmeal moth	Pyralidae	Anon. (1980)
Pyralis farinalis (Linnaeus)	Meal snout moth	Pyralidae	Anon. (1980)
Sathrobrota (=*Pyroderces*) *rileyi* (Walsingham)	Pink scavenger caterpillar	Cosmopterigidae	Anon. (1980)
Sitotroga cerealella (Olivier)	Angoumois grain moth	Gelechiidae	Anon. (1980)
Tineola bisselliella (Hummel)	Webbing clothes moth	Tineidae	Swenk (1922)

development, the Angoumois grain moth, the Pink scavenger caterpillar, and the European grain moth occur on the standing crop. They may produce serious infestations later in storage (Kishore and Jotwani 1982, Anon. 1980). These examples illustrate the capability of the moth pests in colonizing grains both in the field and in storage where moisture content is favorable.

Moth larvae feed on the germ and endosperm of the grains leading to loss of weight, germination, and nutritive changes. For example, in one study *P. farinalis* on wheat consumed 98% bran, 100% germ, and 95% of the endosperm; *E. cautella* consumed 40% bran, 90% germ, and 82% endosperm; and *P. interpunctella* consumed 100% bran, 100% germ, and 75% endosperm. The mass loss of wheat infested by *P. farinalis*, *E. cautella*, and *P. interpunctella* was 99.43, 64.22, and 64.03%, respectively (Madrid and Sinha 1982). Demianyk and Sinha (1981) reported that wheat infested with *P. interpunctella* and *E. cautella* resulted not only in decreased germination, but increased microfloral levels. Field infestation losses of corn as measured by damaged kernels due to the pink scavenger caterpillar, *S. rileyi*, over a period of 3 yr ranged from 0.4 to 1.8% on 31 dent corn hybrids (McMillian *et al.* 1976). Nutritive changes in infested grain often are deleterious including a loss of caloric value. For example, corn grains damaged by *S. cerealella* showed an increase in protein content from 0.27 to 1.73%, whereas the % decrease of total sugar, reducing sugar, starch and oil content ranged from 0.08 to 0.37, 0.01 to 0.21, 0.07 to 1.89, and 0.013 to 0.179, respectively (Pandey and Pandey 1977). Decreases in free fatty acids of wheat infested with *P. interpunctella* and *E. cautella* have been reported by Demianyk and Sinha (1981).

Indirect damage by these pests may result in contamination of the grains with excreta, webbing, and body fragments. Infestation by moth larvae may also lead to increase in grain temperature. A temperature increase of the infested material (wheat feed: yeast: and glycerol, 10:1:2 w/w/w) due to mature *E. cautella*, *E. kuehniella*, and *P. interpunctella* was 7°, 7°, and 5°C, respectively for each species when reared at 25°C (Bell 1976 a). The increase in temperature in the above cases was greater with increasing larval densities and older larvae.

Damage to stored grain by moth pests increases with duration of storage and is also influenced by the type of food commodity. Different foods influence the developmental time and fecundity of stored grain insects thus contributing to differential infestations and damage. For example, the almond moth, *E. cautella*, developed in the shortest time on sorghum requiring 32 days from egg to adult, but required 39, 58, and 37.4 days on groundnuts, linseed, and maize, respectively. However, the number of eggs laid per female was 167.3 on sorghum, a significantly lower value than eggs laid by females reared on groundnut (223.8 eggs) and linseed (221.1 eggs) (Mookherjee *et al.* 1969).

Interestingly, two moth species, *H. pseudospretella* and *E. sarcitrella* have been reported causing structural damage to plaited wood work in a textile industry (Walchli 1972).

Monetary losses due to moth infestations can occur at the time of sale as discounts applied by the grain buyer. In Minnesota, discounts applied to corn and wheat due to the presence of stored grain insects averaged 5.3 cents and 7 cents/bushel, respectively (Barak and Harein 1981).

Besides attacking stored grain, several species of moths also attack several other stored commodities such as nuts, flour, coffee beans, cocoa, and dried fruits. The meal snout moth, *P. farinalis*, and *E. elutella*, and *E. figulilella* attack macadamia nuts (Fletcher 1976), tobacco (Meyer 1980), and dried fruits (Amos *et al.* 1980), respectively. The Indianmeal moth, *P. interpunctella*, has been recorded on dried figs in warehouses (Erakay and Ozar 1979), prunes (Torch 1977), and sunflower seeds (Delaney 1978); *E. cautella* successfully completes development on sesamum seed (Heape 1969), soybeans, groundnut, tamarind (Kapoor *et al.* 1972), and cocoa (Okobi 1978). The European grain moth, the whiteshouldered house moth, and the rice moth have been reported attacking stored walnuts (Smith 1960), oilseed rape (Anon. 1983), and processed coffee (Bitran and Oliviera 1978), respectively. Also, *E. kuehniella*, *E. cautella*, *P. interpunctella*, *S. cerealella*, *E. elutella*, *C. cephalonica*, and *P. farinalis* are common pests of flour (Buchelos 1980). The losses contributed by moth pests, therefore, can be extensive considering their damage capability and wide food adaptability. Control of pests is, therefore, necessary to save the grain from losses both in quantity and quality.

II. Disadvantages and limitations in the present methods of chemical control

a) Malathion resistance

Chemical control of insects in storage has been used more as a substitute rather than as a supplement to the non-chemical methods such as sanitation and aeration (Harein and de las Casas 1974). Malathion largely replaced synergized pyrethrins after the 1960s as a residual grain protectant. Initially, malathion was effective against grain infesting moths (LaHue 1966, 1975, Nelson *et al.* 1963, Spitler and Hartsell 1967, 1969, Spitler *et al.* 1974, Spitler and Clark 1970). A fuller appraisal of malathion as a grain protectant has been discussed elsewhere (Harein and de las Casas 1974). Increased use of malathion has resulted in the slow development of resistance (Parkin 1965) in several stored grain insects (Champ and Dyte 1977), though a causal relationship between the use of malathion and development of resistance is difficult to establish.

Malathion resistance in several beetles on a worldwide basis was presented by Champ and Dyte (1977). The majority of malathion resistance reports in stored grain Lepidoptera are from the United States and Australia.

Most reports in the United States are concerned with malathion resistance in Indianmeal moth. Zettler *et al.* (1973) have compared the high levels of resistance in the Indianmeal moth with low levels in the almond moth. They also reported that such levels of resistance could not be attributed to resistance to pyrethrins used before the advent of malathion. Malathion resistance in six strains of the Indianmeal moth was > 206-fold, while resistance to pyrethrins ranged from 1.1 to 2.5. Six almond moth strains showed a low level of resistance to malathion (1.2 to 7.2×) as well as to pyrethrins (2.5 to 3.3×). A recent survey in the North Central United States (Beeman *et al.* 1982 a) showed >17× malathion resistance in 39 of the 43 field strains of Indianmeal moths infesting corn. In a survey of moth larvae infesting peanuts in the southern United States Zettler (1982) compared 10 of 12 Indianmeal moth strains and 3 of 9 almond moth strains finding a malathion resistance level of >114-fold and 3.0 to 12.63-fold, respectively. A minimum of >227× resistance to malathion was detected in an Indianmeal moth strain from North Carolina (Bansode *et al.* 1981). Indianmeal moths infesting dried fruits and nuts in California were reported to be malathion resistant and the resistance level was stable even in the absence of any chemical selection (Armstrong and Soderstrom 1975). Malathion resistance in the United States at present appears to be widespread particularly with the Indianmeal moth. Variations in resistance are apparent in different populations and obviously between species.

Malathion resistance among stored grain moth pests in Australia is also widespread. Malathion replaced DDT and lindane as seed protectants and dieldrin and lindane as residuals in storage structures. Attia (1976) reported a >259-fold malathion resistance in two strains of almond moth. A 250-fold minimum resistance in field strains of the Indianmeal moth, almond moth, and a >244-fold resistance in a strain of Mediterranean flour moth were reported by Attia *et al.* (1979) in a separate study. Resistance studies have been largely restricted to a few Pyralid species due probably to their importance and common occurrence in storage.

b) Biochemical basis of malathion resistance

The lack of effective control of malathion resistant populations is due to the presence of malathion-degrading enzymes in many individuals. Specific enzymes are often involved in malathion resistant insects, but not necessarily in all examples. A specific type of malathion resistance is attributed to increased levels of the enzyme carboxylesterase in the gut, fat body, hemolymph, and other organs (Beeman and Schmidt 1982).

Beeman *et al.* (1982) reported increased carboxylesterase activity (5.06 to 12.1) in six field collected strains of the Indianmeal moth varying in their susceptibility to malathion (0 to 44% at a discriminating dose of 20 μg/larva). Enzyme activity increased with reduced susceptibility to malathion, though not linearly. Malathion α-monoacid was the major hydrolysis product, with the malathion α/β-monoacid ratios ranging from 3.4 to 8.1 while in a susceptible strain the ratio was 1.1. Recently, Beeman and Schmidt (1982 b) reported *ca.* 33-fold higher carboxylesterase activity in a highly malathion resistant strain of the Indianmeal moth compared to a susceptible strain.

Indirect evidence of carboxylesterase related malathion resistance was reported by Bansode *et al.* (1981) using the carboxylesterase inhibitor triphenyl phosphate (TPP). Pretreatment (5 hr) of the Indianmeal moth larvae with 1 μl of 10% TPP reduced malathion resistance from >227× to 9.5×. Attia *et al.*

(1979) similarly, have shown that TPP synergises malathion in highly resistant strains of the Indianmeal moth, almond moth, and Mediterranean flour moth; the resistance level was suppressed from a high of >250× to a low of 1.3 to 7.1×. Though these studies lend unequivocal support to specific type of malathion resistance, evidence from responses in some strains of resistant insects to mixed function oxidase inhibitor indicates a non-specific type of malathion resistance. Evidence for this was reported by Attia *et al.* (1979) who did not observe any reduction of LD_{50} values in malathion + TPP treatments against two strains of the Indianmeal moth. This suggests detoxication of malathion by enzymes other than carboxylesterase. However, the synergist S,S,S-tributyl phosphorotrithioate (DEF) increased the toxicity of malathion against two malathion resistance Indianmeal moth strains implying that DEF suppressible esterases play a role in conferring resistance (Attia *et al.* 1980). Synergism of malathion by piperonyl butoxide by a factor of 2.47 in a malathion resistant strain of Indianmeal moth indicated the role of mixed function oxidases in detoxification (Attia 1977). One malathion resistant strain of Indianmeal moth had reduced carboxylesterase levels despite a 200-fold resistance. An explanation involving acetylcholinesterase was not tenable since its activity was unaltered in both susceptible and resistant strains (Zettler 1974 a). Methyl parathion resistant almond moths showed cross-resistance to other dimethyl organophosphates like sumithion, methyl paraoxon, and malathion and not to diethyl compounds such as parathion and EPN (Hashimoto and Fukami 1964, cited in Pasalu *et al.* 1974) lending support to the presence of a non-specific type of malathion resistance.

Genetics of malathion resistance were studied in resistant strains by crosses between susceptible and resistant individuals, followed by backcrosses to a susceptible strain (Crow 1957). Such studies showed the resistance in Indianmeal moths to be controlled by a semidominant gene that is not sex linked (Attia *et al.* 1981, Beeman and Schmidt 1982 b). Increased carboxylesterase levels with decreased α-napthyl acetate esterases suggest the mutation at an esterase gene locus resulting in the biosynthesis of a chemically altered "mutant" enzyme (e.g. carboxylesterase) (Beeman and Schmidt 1982 b). This hypothesis is in agreement with the "mutant aliesterase theory" of Oppenoorth and van Asperen (1960).

In view of the widespread malathion resistance several candidate grain protectants have been evaluated. Among the protectants the following have been shown to be effective against the resistant strains of moths: bioresmethrin (Ardley 1976), synthetic juvenile hormone I (Silhacek *et al.* 1976), dichlorvos (LaHue 1969, Conway 1966, Green *et al.* 1966), and pirimiphos-methyl (Zettler 1974 b, Bansode *et al.* 1981). However, low levels of cross-resistance to pirimiphos-methyl in malathion resistant strains of almond moth and Indianmeal moth were of the magnitude of 7.9 to 12.9× (Attia 1976) and 4.5 to 4.8× (Attia 1977), respectively. Three strains of Indianmeal moth that were 24 to 240-fold malathion resistant were also cross-resistant to fenitrothion (7.2 to 8.6×), and dichlorvos (2.9 to 3.6×). Low levels of tolerance were exhibited by these strains to pyrethrins, pyrethroids (permethrin, *d*-phenothrin, bioresmethrin), and methomyl (Attia 1977). Cross-resistance to the juvenile hormone analogs can be expected as has been documented with house flies (Cerf and Georghiou 1974) and the confused flour beetle, *Tribolium confusum* Jacquelin duVal (Dyte 1972). There is, therefore, a potential for development of resistance in grain infesting moths to the candidate grain protectants currently under evaluation.

c) *Tolerance to fumigants*

Fumigants exert their biocidal activity in the gaseous phase, permeating the food commodity and killing the insects throughout the grain mass. However, fumigants lack prolonged residual effectiveness. Their use varies according to the method of storage of grain and the available methods of application.

Evidence for the development of resistance lacks the extensive documentation previously discussed for malathion. Nevertheless, there is cause for concern with some stored grain Pyralids which are tolerant to methyl bromide and phosphine. Examples of tolerance can be cited with young pupae, eggs, and diapausing larvae. The tolerance of the immature stages also varies with the species. For example, the eggs of *E. elutella* were marginally more tolerant than those of *E. kuehniella, E. cautella,* and *P. interpunctella* to methyl bromide, although 100% mortality occurred at a concentration-time (CT) product of 63 mg h/L. Young pupae (0 to 3 days old) at a temperature of 25 °C required approximately twice the amount of methyl bromide needed to kill the egg stages in all four species of Pyralid moths (Bell 1976 b). Bell (1976 c) reported that the early egg stage of *E. elutella, E. kuehniella, E. cautella,* and *P. interpunctella* were highly tolerant to phosphine. Eggs of *E. elutella* survived a 2-day exposure at a CT product of 142 mg h/L at 25 °C, and an 8-day CT product of 288 mg h/L at 15 °C. In all four species some 0 to 3 day old pupae completed development to adult stage at a CT product of 2.8 mg h/L at 25 °C, but succumbed to a CT product of 1.3 mg h/L when the pupae were more than 3 days old (Bell 1976 c). A greater depression in fecundity and fertility was evident in adults emerging from fumigant surviving pupae than from surviving eggs.

Diapausing larvae of *E. elutella*, and *P. interpunctella* are more tolerant of fumigants. Such larvae of the former species were 8 to 20 times, and the latter 2 to 8 times more tolerant to short exposures of phosphine than non-diapausing larvae (Bell 1977 a).

The degree of tolerance of the diapausing larvae to methyl bromide varies with the species. Diapausing larvae of *E. elutella* survived to adult stage after exposure to CT products of 150 mg h/L at 25 °C and 260 mg h/L at 15 °C, whereas 100% mortality of diapausing *P. interpunctella* larvae occurred at a CT product of 64 mg h/L at 25 °C (Bell 1977 b). However, at cooler temperatures (10° and 15 °C) CT products of 216 and 158 mg h/L, respectively, were required to completely control diapausing larvae of the latter species. In these cases (Bell 1977 b) the CT products were well above the recommended levels commonly accepted for grain disinfestation. Bell and Glanville (1973) suggested an increase in exposure time to control diapausing larvae.

Phosphine for 6 hr at concentrations of 0.7 to 1.4 mg/L at 20 °C was ineffective against *E. elutella*. However, the CT product required for 50% mortality decreased with increased duration of exposure. The final concentration of the fumigant after a 10-day exposure period was 0.02 mg/L with a CT product of 4.6 mg h/L (Bell and Glanville 1973). The extent of diapause among populations (Bell 1976 d) may be sufficient to limit the expected control by the fumigant. However, cost of fumigation increases as more fumigant is required to control tolerant individuals. The use of increased dosages may lead to undesirable and excessive residues in the food grains fumigated (Monro *et al.* 1972). Insect tolerance to specific fumigants may appear in subsequent generations as has been documented with the granary weevil, *Sitophilus granarius* (L.) to carbon dioxide (Bond and Buckland 1979).

It is apparent that stage-specific and diapause-specific tolerant individuals surviving fumigation may be the source of increased insect populations causing unexpected damage.

d) *Factors affecting insecticide efficacy*

Several other factors such as the relative toxicities of the insecticides, relative susceptibilities of the insects species and life stages, and the breakdown of insecticide deposits on grains result in ineffective insect control. These will be discussed individually.

1. Relative toxicity of insecticides.—All insecticides are not equally toxic to a particular life stage or an insect species. For example, 19 to 20 day old larvae of *C. cautella* were highly susceptible to phosphine followed by methyl bromide, ethylene dibromide, carbon disulphide, and ethylene dichloride:carbon tetrachloride (EDCT) (3:1) mixture (Dhaliwal 1974). Phosphine was *ca.* 1545 times more toxic at the LD_{50} level than the EDCT mixture to the larvae. Relative susceptibility ratios for *E. cautella*, *P. interpunctella*, *E. kuehniella*, *E. figulilella*, and *E. elutella* calculated from LC_{95} concentrations required for the least susceptible of the five species indicated dichlorvos to be the most toxic and abate the least toxic (Strong 1960). A comparison involving several candidate insecticides against adult *P. interpunctella* showed pirimiphos-methyl and *d-trans*-resmethrin to be highly toxic compared with dichlorvos, synergized pyrethrins, and malathion (McDonald and Press 1973).

Certain stages of insects are more susceptible than others to a particular insecticide. Adults of *C. cautella* were more susceptible to phosphine than the larval stages. The concentration (mg/L) of the fumigant at LD_{50} was 158.5 for the adults and 251.2 for the larvae during a 6 hr exposure period (Doharey and Khalsa 1976).

Studies on comparative toxicities of insecticides are important in assessing the potential of an insecticide as a control agent, but highly toxic insecticides are limited in their use if they do not possess ideal characteristics regarding their safety. On the other hand an insecticide possessing ideal characteristics such as low mammalian toxicity may be discouraged from use if increased dosages are required to kill the target pests leading to increased cost of treatments and residue problems.