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A COMPARISON OF BIORESMETHRIN, CHLORPYRIFOS-METHYL AND PIRIMIPHOS-METHYL AS GRAIN PROTECTANTS AGAINST MALATHION-RESISTANT INSECTS IN WHEAT

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SUMMARY

Impregnated paper assays and sprayed grain assays were used to characterize the potency of candidate grain protectants against malathion resistant and susceptible *Sitophilus oryzae* (Linnaeus), *Rhyzopertha dominica* (Fabricius) and *Tribolium castaneum* (Herbst). Malathion-resistant *Ephestia cautella* (Walker) were also used in later bioassays.

Resistance factors for malathion as measured by impregnated paper assays were x 4 and x 9 for *S. oryzae*, x 6 for *R. dominica* and x 39 for *T. castaneum*.

Of the synthetic pyrethroids, bioresmethrin was clearly more potent than bioallethrin or tetramethrin and later work involved only bioresmethrin. All synthetic pyrethroids were particularly potent against *R. dominica*. The organophosphorus materials were ranked in descending order of potency—chlorpyrifos-methyl, pirimiphos-methyl and malathion—and were relatively less potent against *R. dominica*.

A level of cross resistance was demonstrated in resistant strains with respect to newer compounds but their high potency indicated the possibility of effective pest control at acceptable dose rates for the present.

Stability of the compounds was investigated by exposing treated wheat to conditions in the upper layers of a grain bulk for intervals up to 25 weeks. Combinations of chlorpyrifos-methyl or pirimiphos-methyl with bioresmethrin are suggested for use as grain protectants, subject to the necessary international approvals of residues.

I. INTRODUCTION

Wheat, barley, oats and sorghum exported from Australia are required by legislation to meet a nil tolerance for live insects. In Queensland, at least 10 species may be major pests of stored grain and grain products and this high standard with regard to insect infestation has been met hitherto largely through the use of malathion as a grain protectant. However, malathion-resistant

strains have developed, initially in *Tribolium castaneum* (Herbst) (Champ and Campbell-Brown 1970) and later in all major species, and are now widespread in the grain-growing areas of the State (unpublished Departmental records). An alternative and effective grain protectant was therefore urgently required.

The malathion protectant has normally been incorporated into the grain during intake into central storage. Pilot usage commenced in 1962 and the treatment has been almost universal since 1965. Of the major pest species *Sitophilus oryzae* (Linnaeus) and *T. castaneum* were initially well controlled. *Rhyzopertha dominica* (Fabricius) was suppressed but *Ephestia cautella* (Walker) increased in importance and generally necessitated alternative control measures. With increasing malathion-resistance levels, *T. castaneum* has now become the most prevalent species and *R. dominica* the most destructive.

Relatively few insecticides have sufficiently low mammalian toxicity to allow their use as grain protectants. While considerable information is available on these insecticides *per se*, relatively little has been published regarding their use in grain. Of the materials considered in the current study, Ardley and Desmarchelier (1974) reported promising results with synergised bioresmethrin on wheat. LaHue (1975) reported promising results with pirimiphos-methyl on wheat and maize and Weaving (1975) reported work on maize and sorghum.

In 1971, investigations were commenced to evaluate potentially useful grain protectants on wheat against these four species with particular reference to malathion-resistant strains.

II. MATERIALS

INSECTICIDES. The following formulations and percentages of active constituents were used in the various experiments—

Insecticide	Technical Material	Emulsifiable Concentrate
bioallethrin	93% w/w	..
bioresmethrin	94% w/w	10% w/v
chlorpyrifos-methyl	95·6% w/w	24% w/v
malathion	97·8% w/w	103% w/v
pirimiphos-methyl	91% w/w	25% w/v
tetramethrin	90% w/w	..

WHEAT. All wheat used was classified as Australian Standard White. That used in culturing test insects or for insecticide treatment was tested and proved pesticide free. It was conditioned to 12% moisture content before use.

TEST INSECTS. The designation of strains in this paper follows a system informally agreed upon among entomological workers in this field in Australia. The initial letter, Q, denotes a Queensland Department of Primary Industries strain number, while C denotes a CSIRO number. The second and third letters indicate the genus and species.

1. *S. oryzae.* Test insects were reared in wheat at 25°C and 70% relative humidity and were aged from 1 to 4 weeks at the commencement of bioassays.

Strain QSO LS2—Susceptible to both lindane and malathion; originally from a single pair selection (Champ and Cribb 1965).

Strain QSO 56—Malathion-resistant, resistance factor in assays with insecticide-impregnated paper x 3.5; originally collected at Brisbane, May 1971.

Strain CSO 231—Malathion-resistant, x 8.9; originally collected in Western Australia, 1971. (Champ personal communication.)

2. *R. dominica.* Test insects were reared at 30°C and 70% R.H. in whole wheat and were 1 to 4 weeks old at the commencement of bioassays.

Strain QRD 14—Malathion-susceptible; originally collected at Oakey, June 1971.

Strain QRD 2—Malathion-resistant, x 5.8; originally collected at Brisbane, August 1970.

3. *T. castaneum.* Test insects were reared at 30°C and 70% R.H. in whole wheat flour and were aged from 1 to 4 weeks at the commencement of the bioassays.

Strain QTC 39—Malathion-susceptible; originally collected at Kumbia, 1969.

Strain QTC 34—Malathion-resistant, x 39.4; originally collected at Oakey, May 1971.

4. *E. cautella.* Test insects were reared in media containing glycerine, yeast and cracked wheat at 25°C and 70% R.H. Eggs used were from 0 to 24 h old at the commencement of bioassays.

Strain QEC 1—Malathion-resistant; originally collected at Brisbane, November 1969.

III. METHODS

BIOASSAYS WITH INSECTICIDE-IMPREGNATED PAPERS. The response of the various strains of Coleoptera to each of the candidate materials was characterized using the method for measurement of insecticide resistance in *S. oryzae* by Champ (1968). This involves exposure of adult insects to insecticide-impregnated papers using technical grade insecticide. For *T. castaneum,* the test interval was 5 h and for *R. dominica* 24 h. Insects were 1 to 4 weeks old at the commencement of bioassays.

ASSAYS WITH INSECTICIDE-TREATED WHEAT. The response of the various strains of Coleoptera were also characterized using insecticide-treated wheat. Batches of wheat, each 500 g, were sprayed in the laboratory with an emulsifiable concentrate formulation diluted with a 1:4 mixture of water and acetone for a total volume of 5 ml.

Spraying was carried out with a Paache Type H air brush sprayer fitted with a No. 5 nozzle, operating at 100 kPa. To ensure maximum deposit of spray particles, the wheat was spread in a funnel on a sieve of 300 mm diameter through which air was slowly drawn by vacuum. The grain was agitated after each one third of the insecticide was applied and each jar was shaken by hand for 1 min after application.

Sprayed grain was placed immediately in glass bottles and edge sealed by molten paraffin with Whatman No. 29 filter papers.

Preliminary studies with malathion indicated that the amount deposited on the grain as measured by gas chromatography exceeded 90% of the quantity applied.

In the case of *S. oryzae,* the inner neck of the jar was treated with an aqueous dispersion of polytetrafluoroethylene 'Fluon GP1' to prevent insects from escaping.

There were three replications of each treatment and samples were stored at 25°C and 70% R.H.

Test insects were added 16 to 24 h later and mortalities were recorded after 3 days in treated grain.

RESIDUAL EFFICACY UNDER BULK STORAGE CONDITIONS. The residual efficacy of the insecticides on treated grain was measured by a series of bioassays and chemical analyses on samples of wheat held in the surface layers of a grain bulk.

Treatment of wheat. Batches of wheat, each 24 kg, were sprayed with 20 ml aliquots of water emulsions to approximate the rate of application used in industry throughout Australia. Each batch was turned in a concrete mixer during spraying and for a further 2 min. The wheat was then placed in jute bags and subsequently buried in the surface layers of a grain bulk.

These grain bulks were in Perrin type horizontal storages which are steel-framed buildings clad with galvanized iron and having a concrete floor.

Three experiments were undertaken during the summer of 1972-73 in the State Wheat Board storages at Baigin, Kaimkillenbun and Macalister respectively. In each experiment, three replicates of each treatment were used set out in the form of a randomized block design.

Bioassays of treated grain. For each assay, 100 test insects were counted into 167 g of treated grain in a 500 ml jar. Jars were sealed with filter paper lids throughout the test and held at 25°C and 70% R.H. Mortalities were assessed at 3 days and surviving insects were returned to the grain. Mortalities of these remaining insects were assessed at 26 days, when all adult insects were removed.

Jars with *S. oryzae* were then returned to 25°C, 70% R.H. and those with *R. dominica* were transferred to 30°C and 70% R.H. The arbitrarily defined F_1 progeny were counted at 10 weeks and all adults were removed. The arbitrary F_2 progeny were counted at 16 weeks and the test was then terminated.

In some cases, where high numbers of F_1 progeny were present, the F_2 assessment was dispensed with because of expected overcrowding.

In all instances, parallel tests were conducted with untreated wheat of the same origin—cool stored at 15°C to prevent insect development.

Chemical analyses. Chemical analyses for the organophosphorous insecticides were carried out by gas chromatography using the method of Elms (1967).

STATISTICAL ANALYSES. Where appropriate, data were analysed by probit and relative potency analyses (Finney 1971). Before the chi-square test in these analyses, adjacent classes were grouped where necessary to equal or exceed 2 as the minimum number expected to respond. Where testing indicated that the log-dose probit mortality lines were not parallel, formal relative potency analyses were not justified. The ratios of equally effective doses obtained by simple division for the LC50 and LC99.9 levels were substituted and no fiducial limits were calculated.

Relative potency analyses are strictly valid only in relation to groups of similar pesticides. Occasionally, to simplify some particular point of the discussion, the term 'relative potency by simple division' has been used to refer to calculations of this nature with unrelated pesticides. The term 'potency ratio' was used to describe the ratio of equally effective doses obtained by two different testing techniques.

In the studies on the residual efficacy of insecticides on treated grain, all mortalities were adjusted for control mortality using Abbott's formula. The percentage response at 26 days was calculated by dividing the sum of the number responding at 3 days and the number responding at 26 days by the sum of the number dead at 3 days and the total present at 26 days. Adjustments were then made for the control mortalities.

In untreated grain, the potential number of F_2 progeny was greater than could develop in the quantity of grain used in the test. Adjustments were first made by simple proportion to allow for the small variation from the nominal 100 parent insects. The number of F_2 progeny in untreated controls was then estimated by assuming the same proportion increase in the F_2 as in the F_1 using the formula—

$$\text{Number of } F_2 = \frac{(\text{number of } F_1)^2}{100}$$

IV. RESULTS AND DISCUSSION

ASSAYS WITH INSECTICIDE-IMPREGNATED PAPERS. Results of probit analyses of data from impregnated paper assays are summarized in table 1, resistance factors in table 3 and relative potencies in table 4.

The malathion-resistance factors estimated for the Queensland strains, that is, x 4 for *S. oryzae,* x 6 for *R. dominica,* x 39 for *T. castaneum,* were typical of the strains currently occurring in the field in Queensland. None of the pairs of regression lines for susceptible and resistant strains was parallel, reflecting the fact that both the resistance levels and the spread in tolerance to the insecticide had increased. Studies on the genetics of the resistant strains were outside the scope of the current work.

The intrinsic potency of the newer materials to the species under study was reflected in their relative potency with respect to malathion, for malathion-susceptible strains.

Chlorpyrifos-methyl was the most potent with relative potencies of x 3, x 3 and x 5 at the LC50 level for *S. oryzae, R. dominica* and *T. castaneum.* Bioresmethrin was specially potent to *R. dominica* with relative potencies by simple division, of x 1·3, x 8·2 and x 0·4. Pirimiphos-methyl was generally less potent than malathion with values of x 0·7, x 0·6 and x 0·8.

Considering this relatively poor result, it is significant that pirimiphos-methyl is relatively volatile (vapour pressure $1{\cdot}1 \times 10^{-4}$ Torr at 30°C), and volatile compounds are disadvantaged by the test involved. The impregnated paper assay allowed loss of the pesticide by volatilization before commencement of the assay and also could not produce accumulation of vapour during the assay.

The malathion-resistant strains of all three species also possessed a low level of cross-resistance to chlorpyrifos-methyl, usually a factor of x 2. Cross-resistance to pirimiphos-methyl was generally slight with the exception of *S. oryzae* strain CSO 231 from Western Australia for which a cross-resistance of x 4 was estimated. Among the synthetic pyrethroid insecticides, a significant feature was again the level of cross-resistance demonstrated by CSO 231—approximately x 4 for both bioallethrin and bioresmethrin, and x 3 for tetramethrin. Factors of x 4, x 2 and x 7 apply also for *T. castaneum.* Interestingly, the malathion-resistant strain of *R. dominica* appeared somewhat more susceptible than the malathion-susceptible strain.

TABLE 1

RESPONSE OF MALATHION-SUSCEPTIBLE AND RESISTANT GRAIN INSECTS IN IMPREGNATED PAPER ASSAYS

Species	Strain	Parameter	Organophosphorous insecticides		
			chlorpyrifos-methyl	malathion	pirimiphos-methyl
Sitophilus oryzae	QSO LS2 .. susceptible	LC50 (5% limits)	0·017(0·016–0·018)	0·053(0·051–0·055)	0·077(0·075–0·078)
		LC99·9 ..	0·048	0·110	0·134
		b	6·9	9·7	12·6
	QSO 56 .. resistant	LC50 (5% limits)	0·034(0·033–0·036)	0·187(0·180–0·194)	0·083(0·079–0·087)
		LC99·9 ..	0·080	0·528	0·219
		b	8·5	6·8	7·3
	CSO 231 .. resistant	LC50 (5% limits)	0·048(0·046–0·050)	0·470(0·420–0·520)	0·309(0·288–0·332)
		LC99·9 ..	0·168	4·314	1·443
		b	5·7	3·2	4·6
Rhyzopertha dominica	QRD 14 .. susceptible	LC50 (5% limits)	0·047(0·043–0·050)	0·123(0·115–0·132)	0·218(0·204–0·237)
		LC99·9 ..	0·277	0·615	1·013
		b	4·0	4·4	4·6
	QRD 2 .. resistant	LC50 (5% limits)	0·083(0·078–0·088)	0·706(0·655–0·764)	0·273(0·247–0·314)
		LC99·9 ..	0·497	5·587	1·575
		b	4·0	3·4	4·1
Tribolium castaneum	QTC 39 .. susceptible	LC50 (5% limits)	0·010(0·009–0·010)	0·050(0·048–0·053)	0·068(0·062–0·074)
		LC99·9 ..	0·037	0·168	0·317
		b	5·2	5·9	4·6
	QTC 34 .. resistant	LC50 (5% limits)	0·022(0·020–0·023)	1·977(1·765–2·181)	0·072(0·068–0·076)
		LC99·9 ..	0·070	28·211	0·318
		b	6·1	2·7	4·8

Concentrations expressed as % w/v active ingredient in total solvent

TABLE 1—continued

RESPONSE OF MALATHION-SUSCEPTIBLE AND RESISTANT GRAIN INSECTS IN IMPREGNATED PAPER ASSAYS—*continued*

Species	Strain	Parameter	Synthetic pyrethroid insecticides		
			bioallethrin	bioresmethrin	tetramethrin
Sitophilus oryzae	QSO LS2 .. susceptible	LC50 (5% limits)	0·421(0·395–0·450)	0·041(0·039–0·043)	0·353(0·327–0·378)
		LC99·9 ..	2·380	0·143	2·155
		b	4·1	5·7	3·9
	QSO 56 .. resistant	LC50 (5% limits)	0·353(0·327–0·380)	0·037(0·035–0·038)	0·460(0·430–0·491)
		LC99·9 ..	2·574	0·128	2·456
		b	3·6	5·7	4·2
	CSO 231 .. resistant	LC50 (5% limits)	1·855(1·581–2·126)	0·175(0·163–0·187)	1·027(0·971–1·085)
		LC99·9 ..	21·179	1·085	4·244
		b	2·9	3·9	5·0
Rhyzopertha dominica	QRD 14 .. susceptible	LC50 (5% limits)	0·055(0·051–0·062)	0·015(0·014–0·016)	0·043(0·041–0·046)
		LC99·9 ..	0·294	0·089	0·178
		b	4·3	4·0	5·0
	QRD 2 .. resistant	LC50 (5% limits)	0·037(0·034–0·039)	0·015(0·014–0·015)	0·028(0·026–0·030)
		LC99·9 ..	0·187	0·046	0·147
		b	4·4	6·2	4·3
Tribolium castaneum	QTC 39 .. susceptible	LC50 (5% limits)	0·358(0·332–0·385)	0·144(0·130–0·165)	0·682(0·503–0·822)
		LC99·9 ..	2·806	0·964	21·948
		b	3·5	3·7	2·0
	QTC 34 .. resistant	LC50 (5% limits)	1·342(1·241–1·451)	0·245(0·229–0·263)	4·582(3·937–5·437)
		LC99·9 ..	10·219	1·339	310·201
		b	3·5	4·2	1·7

Concentrations expressed as % w/v active ingredient in total solvent

TABLE 2

RESPONSE OF MALATHION-SUSCEPTIBLE AND RESISTANT GRAIN INSECTS IN SPRAYED GRAIN ASSAYS

Species	Strain	Parameter	Insecticide			
			bioresmethrin	chlorpyrifos-methyl	malathion	pirimiphos-methyl
Sitophilus oryzae ..	QSO LS2 .. susceptible	LC50 (5% limits)	2·269(2·091–2·438)	0·145(0·140–0·151)	0·594(0·578–0·609)	0·215(0·210–0·219)
		LC99·9 ..	15·78	0·33	1·33	0·41
		b	3·7	8·8	8·8	10·9
	QSO 56 .. resistant	LC50 (5% limits)	1·954(1·795–2·118)	0·192(0·185–0·200)	2·017(1·970–2·063)	0·262(0·257–0·267)
		LC99·9 ..	10·36	0·37	5·55	0·53
		b	4·3	10·8	7·0	10·1
	CSO 231 .. resistant	LC50 (5% limits)	19·001(16·707–21·196)	0·237(0·232–0·242)	4·913(4·754–5·069)	0·759(0·708–0·814)
		LC99·9 ..	352·03	0·57	17·83	2·23
		b	2·4	8·2	5·5	6·6
Rhyzopertha dominica	QRD 14 .. susceptible	LC50 (5% limits)	0·090(0·085–0·096)	1·367(1·319–1·416)	4·680(4·449–4·903)	3·315(3·197–3·433)
		LC99·9 ..	0·61	5·81	25·50	13·89
		b	3·7	4·9	4·2	5·0
	QRD 2 .. resistant	LC50 (5% limits)	0·145(0·138–0·152)	1·404(1·282–1·509)	33·232(31·440–35·385)	2·968(2·812–3·113)
		LC99·9 ..	0·76	5·59	239·95	9·98
		b	4·3	5·1	3·6	5·9
Tribolium castaneum	QTC 39 .. susceptible	LC50 (5% limits)	1·478(1·404–1·565)	0·212(0·195–0·227)	1·133(1·098–1·166)	0·310(0·301–0·319)
		LC99·9 ..	7·47	0·45	2·62	0·60
		b	4·4	9·4	8·5	10·7
	QTC 34 .. resistant	LC50 (5% limits)	4·685(4·310–5·138)	0·231(0·214–0·247)	15·605(14·098–17·038)	0·195(0·180–0·207)
		LC99·9 ..	26·182	0·46	106·72	0·53
		b	4·1	10·3	3·7	7·1

Mortalities assessed after 3 days' exposure in treated grain of 12% moisture content at 25° C.
Concentrations expressed in parts per million

TABLE 3

INSECTICIDE RESISTANCE FACTORS

Insecticide	Type of assay	*Sitophilus oryzae*			*Rhyzopertha dominica*	*Tribolium castaneum*
		QSO 56 QSO LS2	CSO 231 QSO LS2	CSO 231 QSO 56	QRD 2 QRD 14	QTC 34 QTC 39
Organophosphorous Insecticides						
chlorpyrifos-methyl	impregnated paper ..	2·05(1·94–2·17)	2·83(2·66–3·02)	1·39(LC50) 2·11(LC99·9)	1·78(1·63–1·94)	2·23(2·08–2·40)
	sprayed grain	1·32(1·22–1·43)	1·64(1·57–1·71)	1·23(LC50) 1·52(LC99·9)	1·02(0·94–1·10)	1·08(0·99–1·18)
malathion	impregnated paper ..	3·54(LC50) 4·81(LC99·9)	8·92(LC50) 39·29(LC99·9)	2·52(LC50) 8·17(LC99·9)	5·75(LC50) 9·08(LC99·9)	39·37(LC50) 167·69(LC99·9)
	sprayed grain	3·44(3·23–3·57)	8·27(LC50) 13·42(LC99·9)	2·44(LC50) 3·21(LC99·9)	7·05(6·57–7·61)	13·77(LC50) 40·68(LC99·9)
pirimiphos-methyl	impregnated paper ..	1·08(LC50) 1·63(LC99·9)	4·03(LC50) 10·73(LC99·9)	3·72(LC50) 6·59(LC99·9)	1·20(1·09–1·32)	1·06(0·98–1·15)
	sprayed grain	1·22(1·19–1·26)	3·54(LC50) 5·40(LC99·9)	2·90(LC50) 4·21(LC99·9)	0·87(0·82–0·93)	0·66(0·60–0·71)
Synthetic Pyrethroid Insecticides						
bioallethrin	impregnated paper ..	0·84(0·76–0·93)	4·41(LC50) 8·90(LC99·9)	5·43(4·64–6·33)	0·66(0·58–0·74)	3·74(3·37–4·17)
	sprayed grain	..	..	..	..	..
bioresmethrin	impregnated paper ..	0·90(0·84–0·96)	4·27(LC50) 7·58(LC99·9)	4·77(LC50) 8·49(LC99·9)	0·98(LC50) 0·52(LC99·9)	1·76(1·57–1·95)
	sprayed grain	0·83(0·75–0·93)	8·37(LC50) 22·32(LC99·9)	9·72(LC50) 33·96(LC99·9)	1·56(1·45–1·67)	3·13(2·80–3·48)
tetramethrin	impregnated paper ..	1·29(1·18–1·43)	2·85(2·61–3·11)	2·22(2·04–2·42)	0·66(0·60–0·72)	7·40(5·82–9·90)
	sprayed grain	..	..	..	..	..

Fiducial limits of 5% are given where formal analyses were completed. Where the log dosage/probit mortality lines were not parallel, separate values were calculated for LC50 and LC99·9 levels.

TABLE 4

RELATIVE POTENCIES

Species	Strain	Type of assay	chlorpyrifos-methyl malathion	pirimiphos-methyl malathion	chlorpyrifos-methyl pirimiphos-methyl
Sitophilus oryzae	QSO LS2 ..	impregnated paper ..	3·13(LC50) 2·31(LC99·9)	0·69(0·66–0·73)	4·53(LC50) 2·83(LC99·9)
		sprayed grain	4·09(3·91–4·27)	2·80(2·71–2·89)	1·46(1·37–1·55)
	QSO 56 ..	impregnated paper ..	5·40(5·01–5·82)	2·25(2·11–2·41)	2·40(2·23–2·56)
		sprayed grain	10·48(LC50) 14·95(LC99·9)	7·70(LC50) 10·48(LC99·9)	1·36(1·30–1·43)
	CSO 231 ..	impregnated paper ..	9·79(LC50) 25·61(LC99·9)	1·52(LC50) 2·99(LC99·9)	6·37(5·89–6·82)
		sprayed grain	21·38(20·00–22·80)	6·59(6·14–7·06)	3·23(3·01–3·46)
Rhyzopertha dominica	QRD 14 ..	impregnated paper ..	2·60(2·37–2·86)	0·55(0·50–0·61)	4·70(4·28–5·19)
		sprayed grain	3·42(LC50) 4·39(LC99·9)	1·41(LC50) 1·84(LC99·9)	2·43(2·31–2·55)
	QRD 2 ..	impregnated paper ..	8·43(7·69–9·25)	2·47(2·21–2·75)	3·41(3·09–3·78)
		sprayed grain	23·67(LC50) 42·89(LC99·9)	11·20(LC50) 24·03(LC99·9)	2·06(1·91–2·22)
Tribolium castaneum	QTC 39 ..	impregnated paper ..	5·41(4·90–6·01)	0·77(0·70–0·85)	7·05(6·38–7·80)
		sprayed grain	5·42(5·18–5·68)	3·73(3·54–3·93)	1·45(1·38–1·53)
	QTC 34 ..	impregnated paper ..	91·53(LC50) 404·12(LC99·9)	27·47(LC50) 88·73(LC99·9)	3·40(3·16–3·65)
		sprayed grain	67·47(LC50) 230·98(LC99·9)	80·18(LC50) 199·90(LC99·9)	0·83(0·79–0·97)

Fiducial limits of 5% are given where formal analyses were completed. Where the log dosage/probit mortality lines were not parallel, separate values were calculated for the LC50 and LC99·9 levels.

TABLE 4—continued

RELATIVE POTENCIES—*continued*

Species	Strain	Type of assay	bioresmethrin bioallethrin	bioresmethrin tetramethrin	tetramethrin bioallethrin
Sitophilus oryzae	QSO LS2 ..	impregnated paper ..	10·28(LC50) 16·64(LC99·9)	8·62(LC50) 15·07(LC99·9)	1·19(1·08–1·32)
		sprayed grain	..	..	..
	QSO 56 ..	impregnated paper ..	9·64(LC50) 20·16(LC99·9)	12·54(LC50) 19·23(LC99·9)	0·78(0·71–0·85)
		sprayed grain	..	..	..
	CSO 231 ..	impregnated paper ..	10·98(9·44–13·09)	5·88(LC50) 3·91(LC99·9)	1·81(LC50) 4·99(LC99·9)
		sprayed grain	..	..	..
Rhyzopertha dominica	QRD 14 ..	impregnated paper ..	3·62(3·27–4·02)	2·84(2·64–3·07)	1·27(1·15–1·41)
		sprayed grain	..	..	..
	QRD 2 ..	impregnated paper ..	2·47(LC50) 4·06(LC99·9)	1·90(LC50) 3·19(LC99·9)	1·30(1·18–1·43)
		sprayed grain	..	..	..
Tribolium castaneum	QTC 39 ..	impregnated paper ..	2·44(2·14–2·75)	4·74(LC50) 22·76(LC99·9)	0·53(LC50) 0·13(LC99·9)
		sprayed grain	..	..	..
	QTC 34 ..	impregnated paper ..	5·48(4·94–6·08)	18·67(LC50) 231·75(LC99·9)	0·29(LC50) 0·03(LC99·9)
		sprayed grain	..	..	..

Fiducial limits of 5% are given where formal analyses were completed. Where the log dosage/probit mortality lines were not parallel, separate values were calculated for the LC50 and LC99·9 levels.

TABLE 5

POTENCY RATIOS AT THE LC50 LEVEL FOR IMPREGNATED PAPER AND SPRAYED GRAIN ASSAYS

Species	Strain	Insecticide			
		bioresmethrin	chlorpyrifos-methyl	malathion	pirimiphos-methyl
Sitophilus oryzae ..	QSO LS2 .. susceptible	55·3	8·5	11·2	2·8
	QSO 56 .. resistant	52·8	5·6	10·8	3·2
	CSO 231 .. resistant	108·6	4·9	10·5	2·5
Rhyzopertha dominica ..	QRD 14 .. susceptible	6·0	29·1	38·0	15·2
	QRD 2 .. resistant	9·7	16·9	47·1	10·9
Tribolium castaneum ..	QTC 39 .. susceptible	10·3	21·2	22·7	4·6
	QTC 34 .. resistant	19.1	10·5	7·9	2·7

Because cross-resistance was at low levels, the relative potencies for all materials with respect to the malathion-resistant strains were much higher than for the malathion-susceptible strains.

Among the synthetic pyrethroids, bioresmethrin was clearly more potent than both bioallethrin and tetramethrin for all species and strains. All three pyrethroids were highly active against *R. dominica*, much more so than any organophosphorus insecticide. However, because of the superior potency of bioresmethrin, a decision was made to limit further testing of synthetic pyrethroids to testing bioresmethrin.

ASSAYS WITH INSECTICIDE-TREATED WHEAT. Results of probit analyses of 3-day mortalities of test insects in sprayed grain are given in table 2, resistance factors in table 3, relative potencies in table 4 and potency ratios in table 5.

The resistance factors calculated were broadly comparable with those from the impregnated paper assays with the largest discrepancies occurring at the LC99·9 level, as would be expected. The LC99·9 values of individual materials were one measure of the insecticide's capacity to produce complete control of infestation in the field. The LC99·9 values for malathion were 1·3, 25·5 and 2·6 p.p.m. for susceptible strains of *S. oryzae, R. dominica* and *T. castaneum* and the resistant strains required concentrations of 5·6, 240 and 107 p.p.m. This was consistent with the field situation where infestations of *T. castaneum* and *R. dominica* become readily detectable in bulk grain storages within 2 months of treatment with malathion at 18 p.p.m.

No attempt was made to relate concentrations in impregnated paper assays to concentrations in sprayed wheat so the absolute values of the potency ratios

had little significance. However, comparison of values for different materials provided a convenient means of emphasizing differences in results of impregnated paper assays and sprayed grain assays.

The potency ratios for pirimiphos-methyl were low, indicating that it was more potent in sprayed grain assays than in impregnated paper assays. This is consistent with the hypothesis that the material is active in the vapour phase. The values for bioresmethrin were high with respect to *S. oryzae*, especially the highly malathion-resistant strain CSO 231, indicating that this material was relatively less potent in sprayed grain. Overall, potency ratios tended to be highest where treatments were least effective.

Mortality in sprayed grain assays was assessed after 3 days compared with 5, 7 or 24 h for filter paper assays.

The results are, therefore, consistent with the hypothesis that the test insects were able to metabolize some insecticides up to a maximum rate. Under this hypothesis, the comparatively high dosages in the impregnated paper assays result in the accumulation of insecticide at active sites within the insects at a greater rate than may be detoxified by metabolizing processes. In contrast, the insects metabolize the lower dose of insecticide in sprayed grain before accumulation of a toxic dose.

RESIDUAL EFFICACY UNDER BULK STORAGE CONDITIONS. Data relating to residue levels on treated wheat determined analytically are given in table 6.

In selecting the application rates, the aim was to exercise complete control of test insects at the beginning of the experiment but to allow some control failure before its completion. Dosages were, therefore, lower than would be used in an industrial situation. The half-life of malathion of 9·5 weeks determined here compared with values around 15 to 25 weeks determined by Elms, Kerr and Champ (1972). These authors used a constant temperature of 25°C compared with 30°C' at the commencement of this experiment. Chlorpyrifos-methyl with a half-life of 18 weeks was more persistent than malathion while pirimiphos-methyl was very persistent with a half-life of approximately a year.

Summaries of data on mortality at 3 days, mortality at 26 days and percentage reduction in F_1 and F_2 progeny are given in tables 7 to 16. Analyses of variance carried out as a preliminary indicated that differences between sites were not significant. Data from the three sites have been combined.

Percentage mortality at 3 days was a convenient measure of acute toxicity and the ability of a protectant to produce a rapid kill may be an important factor when the insecticide is used as a disinfestation treatment. In general, effective deposits of the organophosphorous insecticides produced complete 3-day mortality of *S. oryzae* or *T. castaneum* but not of *R. dominica.* In contrast, bioresmethrin produced complete 3-day mortality of *R. dominica* but not of the other species.

Percentage mortality at 26 days measured the ability of adult insects to survive in treated grain. Of particular interest was the finding that, after the initial 4 weeks of the experiment, significant numbers of adult *R. dominica* were able to survive all of the organophosphorous materials. Chlorpyrifos-methyl was the most effective of the organophosphorous materials against *R. dominica.*

Similarly, after the first 8 weeks, there was a tendency for adults of *S. oryzae* and *T. castaneum* to survive in the bioresmethrin treated grain. It was never effective against the relatively resistant strain of *S. oryzae* CSO 231.

TABLE 6

INSECTICIDE RESIDUES IN TREATED WHEAT STORED UNDER BULK STORAGE CONDITIONS BEFORE ASSAY

Treatment	Time after Spray Application						Estimated half-life in weeks
	1 day	2 weeks	4 weeks	8 weeks	16 weeks	25 weeks	
malathion 4 p.p.m.	2·95(2·72–3·17)	2·35(2·16–2·55)	1·99(1·83–2·15)	1·04(0·99–1·09)	0·68(0·59–0·76)	0·81(0·72–0·89)	9·5
pirimiphos-methyl 2 p.p.m.	1·92(1·75–2·10)	2·24(2·04–2·44)	2·04(1·81–2·27)	1·98(1·82–2·14)	1·62(1·36–1·88)	1·62(1·41–1·82)	43·2
pirimiphos-methyl 4 p.p.m.	3·74(3·39–4·09)	3·53(3·31–3·76)	3·95(3·59–4·31)	3·50(3·36–3·63)	2·96(2·78–3·14)	2·94(2·75–3·13)	47·6
chlorpyrifos-methyl 2 p.p.m.	2·10(1·96–2·24)	2·04(1·92–2·16)	2·03(1·88–2·18)	1·42(1·25–1·59)	1·09(1·02–1·16)	1·10(0·86–1·34)	19·6
chlorpyrifos-methyl 4 p.p.m.	4·17(3·31–5·04)	4·00(3·37–4·63)	4·10(3·14–5·06)	2·84(2·30–3·39)	2·11(1·66–2·56)	1·94(1·49–2·39)	18·2

Concentrations in parts per million for means (n=9) and 5% confidence intervals

TABLE 7

PERCENTAGE MORTALITY AT 3 DAYS FOR *Sitophilus oryzae* IN TREATED WHEAT STORED UNDER BULK STORAGE CONDITIONS BEFORE ASSAY

Treatment	Strain	Time after Spray Application					
		1 day	2 weeks	4 weeks	8 weeks	16 weeks	25 weeks
malathion 4 p.p.m.	QSO LS2	100	100	100	100	70·94	26·33
	QSO 56	100	100	98·99	74·82	11·74	1·00
	CSO 231	80·54	22·88	11·29	2·18	0·0	*
pirimiphos-methyl 2 p.p.m.	QSO LS2	100	100	100	100	99·00	99·24
	QSO 56	100	100	100	100	99·52	99·67
	CSO 231	100	88·94	67·59	37·76	2·31	4·07
pirimiphos-methyl 4 p.p.m.	QSO LS2	100	100	100	100	100	100
	QSO 56	100	100	100	100	100	100
	CSO 231	100	100	97·98	92·14	33·84	25·64
chlorpyrifos-methyl 2 p.p.m.	QSO LS2	100	100	100	100	100	98·22
	QSO 56	100	100	100	100	98·16	93·50
	CSO 231	100	100	100	99·83	51·59	34·24
chlorpyrifos-methyl 4 p.p.m.	QSO LS2	100	100	100	100	100	100
	QSO 56	100	100	100	100	100	99·83
	CSO 231	99·84	100	100	100	96·63	89·18
bioresmethrin 4 p.p.m.	QSO LS2	91·55	91·64	45·85	19·61	10·62	3·01
	QSO 56	93·51	82·67	34·83	28·52	1·84	4·94
	CSO 231	4·66	3·53	2·21	0·33	0·0	*
bioresmethrin 8 p.p.m.	QSO LS2	97·99	99·66	88·01	66·53	15·59	22·85
	QSO 56	99·50	98·49	91·80	80·25	4·54	28·87
	CSO 231	19·04	25·94	7·05	2·17	0·17	*

* Assay not undertaken because of treatment failure at earlier sampling date.

TABLE 8

PERCENTAGE MORTALITY AT 26 DAYS FOR *Sitophilus oryzae* IN TREATED WHEAT STORED UNDER BULK STORAGE CONDITIONS BEFORE ASSAY

Treatment	Strain	Time after Spray Application					
		1 day	2 weeks	4 weeks	8 weeks	16 weeks	25 weeks
malathion 4 p.p.m.	QSO LS2 ..	100	100	100	100	100	100
	QSO 56 ..	100	100	100	100	76·04	63·58
	CSO 231 ..	100	97·93	87·77	60·41	8·40	*
pirimiphos-methyl 2 p.p.m.	QSO LS2 ..	100	100	100	100	100	100
	QSO 56 ..	100	100	100	100	100	100
	CSO 231 ..	100	100	100	100	81·11	24·59
pirimiphos-methyl 4 p.p.m.	QSO LS2 ..	100	100	100	100	100	100
	QSO 56 ..	100	100	100	100	100	100
	CSO 231 ..	100	100	100	100	100	100
chlorpyrifos-methyl 2 p.p.m.	QSO LS2 ..	100	100	100	100	100	100
	QSO 56 ..	100	100	100	100	100	100
	CSO 231 ..	100	100	100	100	100	84·34
chlorpyrifos-methyl 4 p.p.m.	QSO LS2 ..	100	100	100	100	100	100
	QSO 56 ..	100	100	100	100	100	100
	CSO 231 ..	100	100	100	100	100	100
bioresmethrin 4 p.p.m.	QSO LS2 ..	99·68	99·20	98·66	97·30	37·39	28·79
	QSO 56 ..	100	100	99·84	100	48·57	49·16
	CSO 231 ..	59·02	29·77	12·83	4·65	2·35	*
bioresmethrin 8 p.p.m.	QSO LS2 ..	100	99·89	99·22	99·07	96·92	91·90
	QSO 56 ..	100	100	100	100	98·98	97·59
	CSO 231 ..	87·45	60·05	49·72	20·89	4·25	*

* Assay not undertaken because of treatment failure at earlier sampling date

TABLE 9

PERCENTAGE REDUCTION IN F_1 PROGENY FOR *Sitophilus oryzae* IN TREATED WHEAT STORED UNDER BULK STORAGE CONDITIONS BEFORE ASSAY

Treatment	Strain	Time after Spray Application					
		1 day	2 weeks	4 weeks	8 weeks	16 weeks	25 weeks
malathion 4 p.p.m.	QSO LS2	>99·98 D	99·82	99·92 D	99·26 D	97·61	92·51
	QSO 56	99·74 D	98·95	98·51	96·76	67·42	52·83
	CSO 231	97·02	89·23	84·01	47·61	7·20	*
pirimiphos-methyl 2 p.p.m.	QSO LS2	100	99·97 D	99·96 D	99·83 D	99·34 D	98·16 D
	QSO 56	>99·98 D	99·91 D	99·93 D	99·57 D	99·11 D	97·13 D
	CSO 231	99·68 D	98·31 D	97·93	93·97	66·52	69·05
pirimiphos-methyl 4 p.p.m.	QSO LS2	100	100	100	99·97 D	99·87 D	99·50 D
	QSO 56	>99·98 D	>99·98 D	>99·98 D	99·92 D	99·76 D	98·68 D
	CSO 231	99·97 D	99·41 D	99·47 D	97·86	94·90	91·35
chlorpyrifos-methyl 2 p.p.m.	QSO LS2	>99·98 D	>99·98 D	>99·98 D	99·98 D	99·81 D	98·77 D
	QSO 56	100	>99·98 D	>99·98	99·82 D	99·26 D	96·65
	CSO 231	100	99·98 D	>99·98 D	99·61 D	97·34	90·97
chlorpyrifos-methyl 4 p.p.m.	QSO LS2	100	100	100	>99·98 D	99·94 D	99·78 D
	QSO 56	100	100	>99·98 D	99·98 D	99·83 D	99·20 D
	CSO 231	100	99·98 D	>99·98 D	99·95 D	99·59 D	98·43
bioresmethrin 4 p.p.m.	QSO LS2	100	100	99·50	93·96	54·39	55·14
	QSO 56	>99·98 D	100	99·86	99·00	55·86	56·52
	CSO 231	75·78	37·21	44·18	10·38	9·69	*
bioresmethrin 8 p.p.m.	QSO LS2	100	>99·98 D	>99·98 D	99·79	94·76	89·38
	QSO 56	>99·98 D	100	>99·98 D	>99·98 D	96·89	94·34
	CSO 231	90·56	73·78	65·62	31·98	21·63	*

D All progeny dead at time of assessment.
* Assay not undertaken because of treatment failure at earlier sampling date.

TABLE 10

PERCENTAGE REDUCTION IN F_2 PROGENY FOR *Sitophilus oryzae* IN TREATED WHEAT STORED UNDER BULK STORAGE CONDITIONS BEFORE ASSAY

Treatment	Strain	Time after Spray Application					
		1 day	2 weeks	4 weeks	8 weeks	16 weeks	25 weeks
malathion 4 p.p.m.	QSO LS2 ..	100	>99·999 D	>99·999 D	99·999 D	99·95	98·71
	QSO 56 ..	99·997 D	99·991	99·95	99·11	*	*
	CSO 231 ..	98·18	94·98	*	*	*	**
pirimiphos-methyl 2 p.p.m.	QSO LS2 ..	100	>99·999 D	100	100	100	99·996 D
	QSO 56 ..	100	100	100	99·999 D	99·997	99·991 D
	CSO 231 ..	99·997 D	99·93	99·90	97·47	*	*
pirimiphos-methyl 4 p.p.m.	QSO LS2 ..	100	100	100	100	100	>99·999 D
	QSO 56 ..	100	>99·999 D	100	>99·999 D	>99·999 D	99·999 D
	CSO 231 ..	>99·999 D	>99·999 D	99·999 D	99·89	99·03	97·42
chlorpyrifos-methyl 2 p.p.m.	QSO LS2 ..	100	100	100	100	>99·999 D	99·998 D
	QSO 56 ..	100	100	100	100	99·997 D	99·95
	CSO 231 ..	100	100	100	99·998 D	99·72	96·83
chlorpyrifos-methyl 4 p.p.m.	QSO LS2 ..	100	>99·999 D	100	100	>99·999 D	100
	QSO 56 ..	>99·999 D	100	100	>99·999 D	>99·999 D	99·998 D
	CSO 231 ..	>99·999 D	100	100	>99·999 D	99·993 D	99·90
bioresmethrin 4 p.p.m.	QSO LS2 ..	100	>99·999 D	99·86	97·89	*	*
	QSO 56 ..	100	100	99·96	99·66	*	*
	CSO 231 ..	*	*	*	*	*	**
bioresmethrin 8 p.p.m.	QSO LS2 ..	100	100	100	99·997	98·66	*
	QSO 56 ..	100	100	100	100	99·10	97·67
	CSO 231 ..	98·00	*	*	*	*	**

D All progeny dead at time of assessment.
* Assay terminated because high numbers of F_1 progeny indicated that overcrowding of F_2 generation would invalidate results.
** Assay not undertaken because of treatment failure at earlier sampling date

TABLE 11

PERCENTAGE MORTALITY AT 3 DAYS FOR *Rhyzopertha dominica* IN TREATED WHEAT STORED UNDER BULK STORAGE CONDITIONS BEFORE ASSAY

Treatment	Strain	Time after Spray Application					
		1 day	2 weeks	4 weeks	8 weeks	16 weeks	25 weeks
malathion 4 p.p.m.	QRD 14 ..	95·76	71·17	..	50·14	34·63	23·62
	QRD 2 ..	9·22	2·98	9·51	7·86	27·70	0·34
pirimiphos-methyl 2 p.p.m.	QRD 14 ..	50·04	69·39	..	4·02	11·49	11·76
	QRD 2 ..	35·20	4·76	17·49	2·33	39·54	4·41
pirimiphos-methyl 4 p.p.m.	QRD 14 ..	94·09	95·19	..	13·08	25·56	24·63
	QRD 2 ..	84·00	51·98	59·72	15·75	62·30	3·72
chlorpyrifos-methyl 2 p.p.m.	QRD 14 ..	99·67	99·32	..	47·29	13·39	9·76
	QRD 2 ..	97·87	86·87	69·10	21·40	47·29	9·17
chlorpyrifos-methyl 4 p.p.m.	QRD 14 ..	99·68	100	..	81·39	35·49	19·79
	QRD 2 ..	99·65	98·67	92·91	67·41	79·60	10·82
bioresmethrin 4 p.p.m.	QRD 14 ..	100	100	..	100	92·25	100
	QRD 2 ..	100	100	100	100	100	100
bioresmethrin 8 p.p.m.	QRD 14 ..	100	100	..	100	100	100
	QRD 2 ..	100	100	100	100	100	100

TABLE 12

PERCENTAGE MORTALITY AT 26 DAYS FOR *Rhyzopertha dominica* IN TREATED WHEAT STORED UNDER BULK STORAGE CONDITIONS BEFORE ASSAY

Treatment	Strain	Time after Spray Application					
		1 day	2 weeks	4 weeks	8 weeks	16 weeks	25 weeks
malathion 4 p.p.m.	QRD 14 ..	100	97·17	..	95·81	91·06	74·06
	QRD 2 ..	17·30	11·38	14·88	14·79	33·05	7·05
pirimiphos-methyl 2 p.p.m.	QRD 14 ..	92·27	86·72	..	38·62	31·48	33·80
	QRD 2 ..	87·38	56·64	58·42	14·57	45·17	11·35
pirimiphos-methyl 4 p.p.m.	QRD 14 ..	100	99·18	..	74·79	79·85	66·40
	QRD 2 ..	98·67	95·13	95·21	75·59	70·95	23·48
chlorpyrifos-methyl 2 p.p.m.	QRD 14 ..	100	100	..	90·54	43·57	35·85
	QRD 2 ..	100	100	100	59·53	49·41	24·47
chlorpyrifos-methyl 4 p.p.m.	QRD 14 ..	100	100	..	99·64	76·37	50·51
	QRD 2 ..	100	100	100	97·53	88·31	37·66
bioresmethrin 4 p.p.m.	QRD 14 ..	100	100	..	100	100	100
	QRD 2 ..	100	100	100	100	100	100
bioresmethrin 8 p.p.m.	QRD 14 ..	100	100	..	100	100	100
	QRD 2 ..	100	100	100	100	100	100

TABLE 13

PERCENTAGE REDUCTION IN F_1 PROGENY FOR *Rhyzopertha dominica* IN WHEAT STORED UNDER BULK STORAGE CONDITIONS BEFORE ASSAY

Treatment	Strain	Time after Spray Application					
		1 day	2 weeks	4 weeks	8 weeks	16 weeks	25 weeks
malathion 4 p.p.m.	QRD 14 ..	100	99·71 D	..	99·56	97·11	97·44
	QRD 2 ..	66·91	74·80	50·48	42·59	0·0	49·19
pirimiphos-methyl 2 p.p.m.	QRD 14 ..	99·72	99·48	..	87·53	26·58	32·90
	QRD 2 ..	99·91	98·62	97·46	86·76	0·0	0·0
pirimiphos-methyl 4 p.p.m.	QRD 14 ..	100	100	..	99·15	92·41	90·71
	QRD 2 ..	100	99·87	99·91	99·29	86·47	66·62
chlorpyrifos-methyl 2 p.p.m.	QRD 14 ..	100	100	..	99·83	95·76	97·27
	QRD 2 ..	100	100	99·88	99·94	97·81	94·43
chlorpyrifos-methyl 4 p.p.m.	QRD 14 ..	100	100	..	100	98·38	98·56
	QRD 2 ..	100	100	100	>99·95	>99·77	99·22
bioresmethrin 4 p.p.m.	QRD 14 ..	100	100	..	100	100	100
	QRD 2 ..	100	100	>99·95 D	100	100	100
bioresmethrin 8 p.p.m.	QRD 14 ..	100	100	..	100	100	>99·79 D
	QRD 2 ..	99·94 D	100	100	100	100	100

D All progeny dead at time of assessment.

TABLE 14

PERCENTAGE REDUCTION IN F_2 PROGENY FOR *Rhyzopertha dominica* IN WHEAT STORED UNDER BULK STORAGE CONDITIONS BEFORE ASSAY

Treatment	Strain	Time after Spray Application					
		1 day	2 weeks	4 weeks	8 weeks	16 weeks	25 weeks
malathion 4 p.p.m.	QRD 14 ..	100	100	..	>99·98	97·86	97·36
	QRD 2 ..	82·62	*	*	*	*	80·03
pirimiphos-methyl 2 p.p.m.	QRD 14 ..	99·96	99·92	..	87·08	0·0	0·0
	QRD 2 ..	99·995	99·51	98·37	92·28	0·0	0·0
pirimiphos-methyl 4 p.p.m.	QRD 14 ..	100	100	..	99·43	93·41	85·76
	QRD 2 ..	100	>99·995 D	100	99·88	46·73	60·16
chlorpyrifos-methyl 2 p.p.m.	QRD 14 ..	100	100	..	100	99·10	95·94
	QRD 2 ..	100	100	100	>99·995	98·84	99·52
chlorpyrifos-methyl 4 p.p.m.	QRD 14 ..	100	>99·99 D	..	100	100	99·61
	QRD 2 ..	100	100	100	>99·995	100	99·89
bioresmethrin 4 p.p.m.	QRD 14 ..	100	>99·99 D	..	100	100	100
	QRD 2 ..	100	100	100	100	100	100
bioresmethrin 8 p.p.m.	QRD 14 ..	100	100	..	100	100	100
	QRD 2 ..	>99·995 D	100	100	100	100	100

D All progeny dead at time of assessment.
* Assay terminated because high numbers of F_1 progeny indicated that overcrowding of F_2 generation would invalidate results.

TABLE 15

PERCENTAGE MORTALITY AT 3 DAYS FOR *Tribolium castaneum* IN TREATED WHEAT STORED UNDER BULK STORAGE CONDITIONS BEFORE ASSAY

Treatment	Strain	Time after Spray Application					
		1 day	2 weeks	4 weeks	8 weeks	16 weeks	25 weeks
malathion 4 p.p.m.	QTC 39 ..	100	100	100	67·88	12·60	0·67
	QTC 34 ..	28·47	33·43	18·16	2·61	1·70	0·0
pirimiphos-methyl 2 p.p.m.	QTC 39 ..	100	100	100	100	97·45	88·78
	QTC 34 ..	100	99·67	99·32	93·43	66·99	55·21
pirimiphos-methyl 4 p.p.m.	QTC 39 ..	100	100	100	100	100	100
	QTC 34 ..	100	100	100	100	94·34	95·67
chlorpyrifos-methyl 2 p.p.m.	QTC 39 ..	100	100	100	100	60·61	35·86
	QTC 34 ..	100	100	100	96·74	16·54	32·33
chlorpyrifos-methyl 4 p.p.m.	QTC 39 ..	100	100	100	100	98·32	91·33
	QTC 34 ..	100	100	100	100	89·99	66·33
bioresmethrin 4 p.p.m.	QTC 39 ..	98·00	90·23	68·28	1·96	5·02	0·67
	QTC 34 ..	95·25	71·58	55·05	0·0	0·67	1·01
bioresmethrin 8 p.p.m.	QTC 39 ..	100	100	99·00	59·49	9·76	12·37
	QTC 34 ..	100	96·00	94·81	30·29	2·01	0·0

TABLE 16

PERCENTAGE MORTALITY AT 26 DAYS FOR *Tribolium castaneum* IN TREATED WHEAT STORED UNDER BULK STORAGE CONDITIONS BEFORE ASSAY

Treatment	Strain	Time after Spray Application					
		1 day	2 weeks	4 weeks	8 weeks	16 weeks	25 weeks
malathion 4 p.p.m.	QTC 39 ..	100	100	100	72·86	78·11	58·42
	QTC 34 ..	46·99	36·47	20·20	13·07	3·88	5·00
pirimiphos-methyl 2 p.p.m.	QTC 39 ..	100	100	100	100	100	100
	QTC 34 ..	100	100	100	100	91·00	90·98
pirimiphos-methyl 4 p.p.m.	QTC 39 ..	100	100	100	100	100	100
	QTC 34 ..	100	100	100	100	100	100
chlorpyrifos-methyl 2 p.p.m.	QTC 39 ..	100	100	100	100	99·66	98·66
	QTC 34 ..	100	100	100	100	92·60	85·48
chlorpyrifos-methyl 4 p.p.m.	QTC 39 ..	100	100	100	100	100	100
	QTC 34 ..	100	100	100	100	100	100
bioresmethrin 4 p.p.m.	QTC 39 ..	100	100	99·32	48·39	41·45	35·95
	QTC 34 ..	100	100	97·67	44·29	12·17	13·44
bioresmethrin 8 p.p.m.	QTC 39 ..	100	100	100	100	83·61	85·61
	QTC 34 ..	100	100	100	97·37	63·48	61·38

TABLE 17

PERCENTAGE REDUCTION IN NUMBER OF ADULTS OF *Ephestia cautella* DEVELOPING FROM EGGS IN TREATED WHEAT STORED UNDER BULK STORAGE CONDITIONS BEFORE ASSAY

Treatment	Time after Spray Application					
	1 day	2 weeks	4 weeks	8 weeks	16 weeks	25 weeks
malathion 4 p.p.m.	2·7	0·0	55·0	0·0	0·0	44·5
pirimiphos-methyl 2 p.p.m.	100	100	100	100	100	100
pirimiphos-methyl 4 p.p.m.	100	100	100	100	100	100
chlorpyrifos-methyl 2 p.p.m.	100	100	100	100	100	98·8
chlorpyrifos-methyl 4 p.p.m.	100	100	100	100	100	100
bioresmethrin 4 p.p.m.	100	100	100	0·0	0·0	54·3
bioresmethrin 8 p.p.m.	100	100	100	100	0·0	67·9

TABLE 18

INTERVAL OF EFFECTIVE GRAIN PROTECTION UNDER BULK STORAGE CONDITIONS

Treatment	*Sitophilus oryzae*			*Rhyzopertha dominica*		*Tribolium castaneum*		*Ephestia cautella*
	QSO LS2	QSO 56	CSO 231	QRD 14	QRD 2	QTC 39	QTC 34	QEC 1
malathion 4 p.p.m.	8 weeks	1 day	none	2 weeks*	none	4 weeks	none	none
pirimiphos-methyl 2 p.p.m.	25 weeks	25 weeks	1 day	none	none	25 weeks	8 weeks	25 weeks
pirimiphos-methyl 4 p.p.m.	25 weeks	25 weeks	4 weeks	2 weeks*	4 weeks	25 weeks	25 weeks	25 weeks
chlorpyrifos-methyl 2 p.p.m. ..	25 weeks	16 weeks	8 weeks	8 weeks	4 weeks	8 weeks	8 weeks	16 weeks
chlorpyrifos-methyl 4 p.p.m. ..	25 weeks	25 weeks	16 weeks	8 weeks	16 weeks	25 weeks	25 weeks	25 weeks
bioresmethrin 4 p.p.m.	2 weeks	2 weeks	none	25 weeks	25 weeks	2 weeks	2 weeks	4 weeks
bioresmethrin 8 p.p.m.	4 weeks	8 weeks	none	25 weeks	25 weeks	8 weeks	4 weeks	8 weeks

* Not tested at 4 weeks

Data on reduction in F_1 and F_2 progeny may conveniently be considered together. The immature stages of *S. oryzae* develop internally in individual grains and are thus partly protected from the insecticide. Adult females introduced into samples treated with an effective grain protectant may oviposit before the insecticide produces mortality and a small F_1 generation may develop. To produce an F_2 generation, the emerging F_1 must mature, mate and spend the preoviposition period in treated grain. Several results indicated that an F_1 generation was produced but no F_2. This particular phenomena does not apply for *R. dominica* where the eggs and first instar larvae live outside the grain. For both species in cases where the insecticide was reasonably effective, the number of individuals in the F_1 generation was so low that a mortality level significantly less than 100% could preclude the production of an F_2 generation.

The percentage reduction in F_2 progeny reported for both species (tables 10 and 14) was generally high. It should be pointed out that it was necessary to discard most samples with less than 95% reduction in F_2 populations for *S. oryzae* and 80% for *R. dominica* because of overcrowding in the test grain. Some assays of *R. dominica* were affected by a predatory mite which reduced numbers in untreated controls. This probably influenced the later results with malathion and pirimiphos-methyl.

Because of the influence of cannibalism, the bioassay test used in this work was not adequate for the estimation of numbers of F_1 progeny of *T. castaneum* and this was not attempted.

Malathion considerably reduced numbers of F_1 and F_2 progeny in *S. oryzae* and *R. dominica* even for the most resistant strains. Pirimiphos-methyl and chlorpyrifos-methyl at 4 p.p.m. both provided an interval in which no progeny developed. Bioresmethrin completely prevented progeny development by *R. dominica* throughout the experiment. It provided a short interval for *S. oryzae* strains from Queensland but never completely controlled the CSO 231 strain.

Data for *E. cautella* (table 17) were based on relatively low numbers of moths and were somewhat variable. Malathion did not produce effective control and this accords with industry experience. Bioresmethrin was effective for 4 weeks while chlorpyrifos-methyl and pirimiphos-methyl were effective throughout the experiment.

The intervals of effective protection for each treatment were estimated for each strain and results are given in table 18. Values for LC100s do not exist statistically and these estimates inevitably involve subjective judgements. Interpretation of data on progeny counts necessitates some allowance for the possibility that an occasional insect parent may be inadvertently carried over due to experimental error. Despite these limitations, the estimates are presented as a guide to the likely performance of the newer protectants under field conditions.

V. GENERAL DISCUSSION

In general, circumstances in the grain industries indicate that a candidate grain protectant for use in Queensland should be capable of affording protection from insect attack for 6 months. Dose rate may be adjusted to suit shortened or extended storage intervals and retreatment may be undertaken if necessary, though at additional cost.

Residues must be of an acceptable nature and must be below prescribed limits at the time of sale. The majority of the grain is exported and residues must be acceptable to the grain importing countries. Under ordinary circumstances, this requires acceptance by the joint FAO/WHO Codex Alimentarius Commission

set up to regulate pesticide residues in raw agricultural products. None of the newer grain protectants evaluated in this study has yet been so accepted and their use may not be authorized until, and unless, the necessary approvals have been obtained.

Within these criteria, the current results indicate that at practicable application rates no one material will exercise adequate control of resistant strains of all the major pest species. Chlorpyrifos-methyl and pirimiphos-methyl, both at 4 p.p.m., gave satisfactory results against *S. oryzae, T. castaneum* and *E. cautella* but not *R. dominica.* Bioresmethrin, at either 4 p.p.m. or 8 p.p.m., was not satisfactory against the first three species but gave satisfactory results against *R. dominica.* Mixtures of bioresmethrin with either of these two materials are suggested for joint control of the species complex. In such a mixture, where bioresmethrin is directed specifically at the control of *R. dominica,* reduction in the dose rate of bioresmethrin is possible. A lower limit of 0.8 p.p.m. is indicated by the LC99.9 for 3-day mortalities in newly sprayed grain, but further work is required to determine the actual optimum.

While effective control of the resistant strains currently known to occur in Queensland would be possible with the proposed mixtures, further development of insecticide resistance is inevitable. Dyte (1974) surveyed the known occurrence of resistances on a world-wide basis and reported it involved 17 species of stored-product pests which, between them, showed resistance to all the main types of insecticides. No easy solution is available but every practicable step should be taken to minimize dependence on insecticides. Increased attention to basic principles of good storage, that is, grain hygiene, reduced moisture and temperature, is urgently required.

Temperature conditions in this study may be regarded as typical of surface layers of bulk wheat and of smaller grain masses such as farm stores in Queensland. However, considerably different conditions apply in large unaerated grain bulks which are insulated from ambient temperature changes because of the low specific thermal conductivity of wheat. Limited observations suggest that these temperatures in Queensland approximate 30°C throughout the storage interval. Moisture conditions also differ between surface layers and other zones and moisture migration may be a significant factor.

Studies to investigate the performance of the newer grain protectants in large grain bulks are currently in progress and will be reported elsewhere.

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