RESULTS AND DISCUSSION

1. Toxicity of phosphine to the tested insects:

The toxicity of phosphine to the insect species tested, which cause serious damage to stored cereal grains and pulses in Egypt namely; Sitophilus oryzae (L.), Rhizopertha dominica (F.) and Callosobruchus maculatus (F.), was determined in the laboratory at 26±1°C, 6±1°C and 60±5% R.H. The fumigation tests were conducted with fixed concentrations of PH_3 (20, 40 and 80 vpm) at varying exposure periods.

1.1. Toxicity of phosphine to all stages of S. oryzae (L.):

The lethal time values and slope of regression lines achieved for the different stages of S. oryzae exposed to various fixed concentrations of phosphine at 26±1°C and 6±1°C are given in Table (1). Results indicate that the lethal time values of all stages required for various levels of mortality were significantly longer at lower temperature than at 26±1°C.

For example, the lethal time value needed to obtain 90% kill of all developmental stages of S. oryzae with a concentration of 20 vpm PH_3 was markedly prolonged from (17, 51, 51 and 122 hr) at 26±1°C to (119, 162, 141 and 261 hr) at 6±1°C for the adult, larval, pupal and egg stage, respectively.

Table (1): Lethal time values and slope of regression line obtained for the different stages of *S. oryzae* (L.) exposed to various fixed concentrations of phosphine at 26±1°C and 6±1°C.

Concentration (vpm)	Stage	Lethal times (hr) at 26±1°C				Slope±SE	Lethal times (hr) at 6±1°C				Slope±SE
		LT_{50}	LT_{90}	LT_{99}	$LT_{99.9}$		LT_{50}	LT_{90}	LT_{99}	$LT_{99.9}$	
20	Adults	10	17	27	38	5.13±0.64	25	119	431	1107	1.87±0.35
	Larvae	9	51	209	588	1.70±0.87	20	162	489	3086	1.41±0.30
	Pupae	13	51	157	361	2.12±0.16	23	141	623	1846	1.62±0.46
	Eggs	38	122	313	625	2.54±0.16	49	261	1029	2807	1.75±0.39
40	Adults	6	16	34	61	3.10±0.51	11	34	82	157	2.71±2.30
	Larvae	8	23	54	101	2.80±0.95	16	88	348	954	1.75±0.78
	Pupae	16	44	101	185	2.90±1.15	11	85	476	1676	1.39±0.20
	Eggs	26	90	249	524	2.37±0.02	37	223	974	2864	1.63±0.34
80	Adults	4	8	14	21	4.40±0.73	8	21	44	78	3.13±1.38
	Larvae	8	32	102	235	2.11±0.03	20	66	180	375	2.40±0.43
	Pupae	11	37	101	209	2.41±2.60	19	60	151	296	2.60±0.02
	Eggs	19	49	108	193	3.02±0.77	29	131	455	1129	1.93±0.74

1 vpm = 1 ppm = 1.413 µg/l.

SE = Standard error of regression line.

With a concentration of 40 vpm PH_3, the lethal exposure value required to achieve 90% mortality was also increased from (16, 23, 44 and 90 hr) at 26±1°C to (34, 88, 85 and 223 hr) at 6±1°C for the forementioned developmental stages, respectively. With a concentration of 80 vpm PH_3, these values were (8, 32, 37 and 49 hr) at 26±1°C and (21, 66, 60 and 131 hr) at the lower temperature. At the LT_{99} and $LT_{99.9}$ levels, the lethal time values of the adult stage were markedly shorter than those of other developmental stages at the two test temperatures. This result intimates that the adult stage of S. oryzae was more susceptible to phosphine than the immature stages.

The lethal response estimates of concentration X time-product (mg.h.l)-required for 50, 90 and 99% kill of all stages of S. oryzae at 26±1°C and 6±1°C are given in Tables (2 and 3). These results show that the mean values of concentration X time in mg.h/l required to obtain 90 and 99% mortalities ($LC.T_{90}$ and $LC.T_{99}$) for the different stages of S. oryzae were significantly lower at higher temperature (26±1°C) than at lower one (6±1°C).

At 26±1°C, the order of tolerance to a phosphine concentration of 20 vpm at the $LC.T_{99}$ level was egg > larva > pupa > adult. The order of tolerance to a phosphine concentration of 40 vpm was egg > pupa > larva > adult. At 80 vpm PH_3 the order of tolerance to phosphine was egg > larva > pupa > adult. The order of tolerance to phosphine

Table (2): Lethal response ($LC.T_{50}$, $LC.T_{90}$ and $LC.T_{99}$) for the different stages of S. oryzae, exposed to various fixed concentrations of PH_3 at 26±1°C and 60±5% RH.

Concentration (vpm)	Stage	Lethal response* (mg.h/l)		
		$LC.T_{50}$	$LC.T_{90}$	$LC.T_{99}$
20	Adults	0.28	0.48	0.76
	Larvae	0.25	1.44	5.91
	Pupae	0.37	1.44	4.44
	Eggs	1.07	3.45	8.85
40	Adults	0.34	0.90	1.92
	Larvae	0.45	1.30	3.05
	Pupae	0.90	2.49	5.71
	Eggs	1.47	5.09	14.07
80	Adults	0.45	0.90	1.58
	Larvae	0.90	3.62	11.53
	Pupae	1.24	4.18	11.42
	Eggs	2.15	5.54	12.21
Mean	Adults	0.36	0.76	1.42
	Larvae	0.53	2.12	6.83
	Pupae	0.84	2.70	7.19
	Eggs	1.56	4.69	11.71

* = Concentration X time products for a certain mortality.

1 vpm = 1 ppm = 1.413 µg/l.

Table (3): Lethal response ($LC.T_{50}$, $LC.T_{90}$ and $LC.T_{99}$) for the different stages of S. oryzae, exposed to various fixed concentrations of PH_3 at 6±1°C and 60±5% RH.

Concentration (vpm)	Stage	Lethal response* (mg.h/l)		
		$LC.T_{50}$	$LC.T_{90}$	$LC.T_{99}$
20	Adults	0.71	3.36	12.18
	Larvae	0.57	4.58	10.99
	Pupae	0.65	3.99	17.61
	Eggs	1.39	7.38	29.10
40	Adults	0.62	1.92	4.64
	Larvae	0.90	4.97	19.67
	Pupae	0.62	4.80	26.90
	Eggs	2.10	12.61	55.10
80	Adults	0.90	2.37	4.97
	Larvae	2.26	7.46	20.35
	Pupae	2.15	6.78	17.10
	Eggs	3.28	14.81	51.40
Mean	Adluts	0.74	2.55	7.26
	Larvae	1.24	5.67	17.00
	Pupae	1.14	5.19	20.54
	Eggs	2.26	11.60	45.20

* = Concentration X time products for a certain mortality.

1 vpm = 1 ppm = 1.413 µg/l.

concentrations ranged from 20-80 vpm was egg > pupa > larva > adult (Table, 2).

At 6±1°C, the order of tolerance to a phosphine concentration of 20 vpm at the LC.T_{99} level was egg > pupa > adult > larva. The order of tolerance to a phosphine concentration of 40 vpm was egg > pupa > larva > adult. With 80 vpm PH_3 the order of tolerance to phosphine was egg > larva > pupa > adult. The order of tolerance to phosphine concentrations ranged from 20-80 vpm was egg > pupa > larva > adult at the LC.T_{99} level (Table, 3).

1.2. Toxicity of phosphine to all stages of R. dominica (F.):

The lethal time values and slope of regression line obtained for all stages of R. dominica exposed to fixed concentrations (20, 40 and 80 vpm) of phosphine at 26±1°C and 6±1°C are shown in Table (4). Data show that the lethal time values of all developmental stages, that required for various levels of mortality were significantly greater at lower temperature than at higher one.

For example, the lethal time value needed to achieve 90% kill of all developmental stages of R. dominica with a phosphine concentration of 20 vpm was markedly increased from (16, 44, 133 and 133 hr) at 26±1°C to (98, 282, 267 and 278 hr) at 6±1°C for the adult, larval, pupal and egg stage, respectively.

Table (4): Lethal time values and slope of regression line obtained for the different stages of *R. dominica* (F.) exposed to various fixed concentrations of phosphine at 26±1°C and 6±1°C.

Concentration (vpm)	Stage	Lethal times (hr) at 26±1°C				Slope±SE	Lethal times (hr) at 6±1°C				Slope±SE
		LT_{50}	LT_{90}	LT_{99}	$LT_{99.9}$		LT_{50}	LT_{90}	LT_{99}	$LT_{99.9}$	
20	Adults	8	16	28	42	4.35±0.51	25	98	300	679	2.13±0.44
	Larvae	16	44	101	188	2.86±1.66	30	282	1771	6785	1.31±0.24
	Pupae	47	133	311	581	2.82±0.06	29	267	1661	6314	1.32±0.19
	Eggs	38	133	369	778	2.36±0.02	59	278	1089	2950	1.76±0.48
40	Adults	7	15	28	45	3.81±0.30	11	30	66	118	3.00±1.92
	Larvae	11	37	100	206	2.42±3.44	23	176	927	3125	1.45±0.28
	Pupae	8	27	68	135	2.56±1.13	18	161	950	3527	1.35±0.11
	Eggs	30	97	253	509	2.52±0.01	22	149	717	2259	1.53±0.10
80	Adults	4	8	14	21	4.40±0.73	10	28	64	118	2.87±1.60
	Larvae	2	20	146	634	1.20±0.23	16	121	631	2113	1.48±0.15
	Pupae	32	98	157	226	4.36±1.60	12	127	908	3822	1.22±0.30
	Eggs	8	37	121	285	2.04±1.16	15	111	559	1823	1.49±0.08

1 vpm = 1 ppm = 1.413 µg/l.

SE = Standard error of regression line.

By a phosphine concentration of 40 vpm, the lethal time value required to give 90% kill was also prolonged from (15, 37, 27 and 97 hr) at the higher temperature to (30, 176, 161 and 149 hr) at the lower one for the forementioned developmental stages, respectively.

With a phosphine concentration of 80 vpm, these values were (8, 20, 98 and 37 hr) at 26±1°C and (28, 121, 127 and 111 hr) at 6±1°C.

At the LT_{99} and $LT_{99.9}$ levels, the lethal exposure values of the adult stage were significantly less than those of the immature stages at the two test temperatures. This result point out that the adult stage of R. dominica was more susceptible to phosphine than the other developmental stages.

The lethal response estimates of concentration X time product in mg.h/l required to obtain 50, 90 and 99% mortality for all stages of R. dominica at 26±1°C and 6±1°C are given in Tables (5 and 6).

These data show that the mean values of concentration X time in mg.h/l needed to achieve 90 and 99% kill ($LC.T_{90}$ and $LC.T_{99}$) for the different stages of R. dominica were markedly greater at 6±1°C than at 26±1°C.

At 26±1°C, the order of tolerance to a phosphine concentration of 20 vpm at the $LC.T_{99}$ level was egg > pupa

Table (5): Lethal response ($LC.T_{50}$, $LC.T_{90}$ and $LC.T_{99}$) for the different stages of R. dominica, exposed to various fixed concentrations of PH_3 at 26±1°C and 60±5% RH.

Concentration (vpm)	Stage	Lethal response* (mg.h/l)		
		$LC.T_{50}$	$LC.T_{90}$	$LC.T_{99}$
20	Adults	0,23	0.45	0.79
	Larvae	0.45	1.24	2.85
	Pupae	0.76	3.76	8.79
	Eggs	1.10	3.76	10.43
40	Larvae	0.40	0.85	1.58
	Larvae	0.62	2.10	5.65
	Pupae	0.45	1.53	3.84
	Eggs	1.70	5.48	14.30
80	Adults	0.45	0.90	1.58
	Larvae	0.23	2.26	15.10
	Pupae	3.30	10.10	16.18
	Eggs	0.80	3.80	12.47
Mean	Adults	0.36	0.73	1.32
	Larvae	0.43	1.81	8.33
	Pupae	1.50	5.13	9.60
	Eggs	1.20	4.35	12.40

* = Concentration X time products for a certain mortality.

1 vpm = 1 ppm = 1.413 µg/l.

Table (6): Lethal response ($LC.T_{50}$, $LC.T_{90}$ and $LC.T_{99}$) for the different stages of *R. dominica*, exposed to various fixed concentrations of PH_3 at 6±1°C and 60±5% RH.

Concentration (vpm)	Stage	Lethal response* (mg.h/l)		
		$LC.T_{50}$	$LC.T_{90}$	$LC.T_{99}$
20	Adults	0.71	2.77	8.48
	Larvae	0.85	7.97	50.05
	Pupae	0.82	7.55	46.94
	Eggs	1.67	7.86	30.80
40	Adults	0.62	1.67	3.73
	Larvae	1.30	9.95	52.40
	Pupae	1.02	9.10	53.70
	Eggs	1.24	8.42	40.50
80	Adults	1.13	3.17	7.23
	Larvae	1.81	12.47	65.00
	Pupae	1.24	13.10	93.60
	Eggs	1.55	11.44	57.60
Mean	Adults	0.82	2.54	6.48
	Larvae	1.32	10.13	55.80
	Pupae	1.03	9.92	64.75
	Eggs	1.49	9.24	42.97

* = Concentration X time products for a certain mortality.

1 vpm = 1 ppm = 1.413 µg/l.

> larva > adult. The order of tolerance to a phosphine concentration of 40 vpm was egg > larva > pupa > adult. With 80 vpm phosphine the order of tolerance was pupa > larva > egg > adult. While the order of tolerance to phosphine concentrations ranged from 20-80 vpm was egg > pupa >larva > adult (Table, 5).

At 6±1°C, the order of tolerance to a phosphine concentration of 20 vpm at the $LC.T_{99}$ level was larva > pupa > egg > adult. With 40 vpm phosphine, the order of tolerance was pupa > larva > egg > adult. The order of tolerance to a phosphine concentration of 80 vpm was pupa > larva > egg > adult. The order of tolerance to phosphine concentrations ranged from 20-80 vpm at the $LC.T_{99}$ level was pupa > larva > egg > adult (Table, 6).

1.3. Toxicity of phosphine to all stages of C. maculatus (F.):

The lethal time values and slope of regression line obtained for the different stages of C. maculatus exposed to various fixed concentrations of phosphine at 26±1°C and 6±1°C are given in Table (7).

Results indicate that the lethal time values of all developmental stages required for various levels of mortality were significantly higher at lower temperature than at higher one.

Table (7): Lethal time values and slope of regression line obtained for the different stages of *C. maculatus* (F.) exposed to various fixed concentrations of phosphine at 26±1°C and 6±1°C.

Concentration (vpm)	Stage	Lethal times (hr) at 26±1°C				Slope±SE	Lethal times (hr) at 6±1°C				Slope±SE
		LT_{50}	LT_{90}	LT_{99}	$LT_{99.9}$		LT_{50}	LT_{90}	LT_{99}	$LT_{99.9}$	
20	Adults	7	22	56	114	2.49±0.17	23	122	487	1337	1.74±0.81
	Larvae	38	67	107	150	5.14±0.02	30	211	1037	3323	1.51±0.15
	Pupae	34	60	94	131	5.27±0.07	18	158	938	3453	1.35±0.31
	Eggs	54	120	209	369	3.69±0.02	50	254	1761	5693	1.50±0.53
40	Adults	9	17	29	42	4.67±0.50	12	74	335	1005	1.60±0.32
	Larvae	27	59	112	179	3.75±0.02	35	119	329	691	2.37±1.62
	Pupae	10	32	80	156	2.67±0.57	10	80	433	1485	1.43±1.23
	Eggs	40	98	204	350	3.26±0.03	31	135	453	1100	1.98±0.49
80	Adults	3	10	28	62	2.25±0.26	6	17	36	66	2.96±0.52
	Larvae	7	27	80	176	2.24±0.42	21	102	370	949	1.87±0.42
	Pupae	49	97	166	247	4.43±0.03	12	67	264	723	1.75±0.77
	Eggs	9	46	173	453	1.32±0.17	16	101	465	1414	1.58±0.13

1 vpm = 1 ppm = 1.413 µg/l. SE = Standard error of regression line.

For example the lethal time value needed to obtain 90% kill of all stages of C. maculatus with 20 vpm was markedly increased from (22, 67, 60 and 120 hr at 26±1°C to 122, 211, 158 and 254 hr at 6±1°C for the adult, larval, pupal and egg stage, respectively. With a concentration of 40 vpm phosphine, the lethal exposure values needed to give 90% kill were also increased from 17, 59, 32 and 98 hr at 26±1°C to 74, 119, 80 and 135 hr at 6±1°C for the forementioned stages, respectively. With the highest concentration of phosphine, these values were 10, 27, 97 and 46 hr at 26±1°C and 17, 102, 67 and 101 hr at 6±1°C for the adult, larval, pupal and egg stage, respectively.

At all various levels of mortalities the lethal time values of the adult stage of C. maculatus were markedly less than the values of the developmental stages at the higher temperature (26±1°C). At the LT_{90} level and 6±1°C, the lethal exposure values of the adult stage were also shorter than the values of immature stages.

Generally, the adult stage of C. maculatus was more susceptible to phosphine than the developmental stages at the two test temperatures and phosphine was most effective at the higher temperature than at the lower one.

The lethal response estimates of concentration X time product in mg.h/l-needed for 50, 90 and 99% mortality

of all stages of C. maculatus at 26±1°C and 6±1°C are shown in Tables (8 and 9). These results indicate that the mean values of concentration X time in mg.h/l required to obtain 90 and 99% mortalities ($LC.T_{90}$ and $LC.T_{99}$) for all stages of C. maculatus were markedly greater at lower temperature than at higher one. This result intimates that phosphine was more effective at the higher temperature than at the lower one.

At 26±1°C, the order of tolerance to a phosphine concentration of 20 vpm at the $LC.T_{99}$ level was egg > larva > pupa > adult. The order of tolerance to a phosphine concentration of 40 vpm was also the same as with 20 vpm. While the order of tolerance to a phosphine concentration of 80 vpm was egg > pupa > larva > adult. Also the same order of tolerance was observed for concentrations between 20-80 vpm.

This result point out that the adult stage of C. maculatus was more susceptible to PH_3 at 26±1°C than the other developmental stages (Table, 8).

At 6±1°C, the order of tolerance to a phosphine concentration of 20 vpm at the $LC.T_{99}$ level was egg > larva > pupa > adult. With a phosphine concentration of 40 vpm, the order of tolerance was egg > pupa > larva > adult.

With a phosphine concentration of 80 vpm, the order of tolerance was egg > larva > pupa > adult, and the order

Table (8): Lethal response ($LC.T_{50}$, $LC.T_{90}$ and $LC.T_{99}$) for the different stages of C. maculatus, exposed to various fixed concentrations of PH_3 at 26±1°C and 60±5% RH.

Concentration (vpm)	Stage	Lethal response* (mg.h/l)		
		$LC.T_{50}$	$LC.T_{90}$	$LC.T_{99}$
20	Adults	0.20	0.62	1.58
	Larvae	1.10	1.89	3.02
	Pupae	0.96	1.70	2.70
	Eggs	1.53	3.39	5.91
40	Adults	0.51	0.96	1.64
	Larvae	1.53	3.33	6.33
	Pupae	0.57	1.80	4.50
	Eggs	2.26	5.54	11.53
80	Adults	0.34	1.13	3.17
	Larvae	0.79	3.05	9.04
	Pupae	5.53	10.90	18.80
	Eggs	1.02	5.20	19.56
Mean	Adults	0.35	0.90	2.13
	Larvae	1.14	2.76	6.13
	Pupae	2.35	4.80	8.67
	Eggs	1.60	4.71	12.33

* = Concentration X time products for a certain mortality.

1 vpm = 1 ppm = 1.413 µg/l.

of tolerance to phosphine concentrations ranged from 20-80 vpm was also egg > larva > pupa > adult at the LC.T_{99} level (Table, 9).

This result indicates that the adult stage of C. maculatus was also the most susceptible stage to phosphine at 6±1°C.

It could be concluded that the adult of S. oryzae (L.), R. dominica (F.) and C. maculatus (F.) proved to be the most susceptible stage to phosphine at 26±1°C or 6±1°C, and the time of exposure was a more critical factor of dosage than the concentration. Phosphine was most effective at higher temperature, against all stages of the insect species, than at the lower one.

With a concentration of 80 vpm phosphine, the times of exposure for 100% mortality in case of S. oryzae, were (0.9, 9.8, 8.7 and 8.0 days) at 26±1°C and (3.3, 15.6, 12.3 and 47.0 days) at 6±1°C for the adult, larval, pupal and egg stage, respectively.

The corresponding values in case of R. dominica were (0.9, 26.4, 9.4 and 11.9 days) at 26±1°C and (4.9, 88, 159.3 and 76 days) at 6±1°C for adult, larval, pupal and egg stage, respectively.

These values in case of C. maculatus were (2.6, 7.3, 10.3 and 18.9 days) at 26±1°C and (2.8, 39.5, 30.1 and

Table (9): Lethal response ($LC.T_{50}$, $LC.T_{90}$ and $LC.T_{99}$) for the different stages of *C. maculatus*, exposed to various fixed concentrations of PH_3 at 6±1°C and 60±5% RH.

Concentration (vpm)	Stage	Lethal response* (mg.h/l)		
		$LC.T_{50}$	$LC.T_{90}$	$LC.T_{99}$
20	Adults	0.65	3.45	13.76
	Larvae	0.85	5.96	29.30
	Pupae	0.51	4.47	26.50
	Eggs	1.41	7.18	49.80
40	Adults	0.68	4.18	18.93
	Larvae	1.98	6.73	18.60
	Pupae	0.57	4.50	24.50
	Eggs	1.75	7.63	25.60
80	Adults	0.68	1.92	4.10
	Larvae	2.37	11.53	41.80
	Pupae	1.36	7.57	29.80
	Eggs	1.81	11.42	52.60
Mean	Adults	0.67	3.18	12.26
	Larvae	1.73	8.07	29.90
	Pupae	0.81	5.51	26.93
	Eggs	1.66	8.74	42.67

* = Concentration X time products for a certain mortality.

1 vpm = 1 ppm = 1.413 µg/l.

58.9 days) at 6±1°C for the forementioned developmental stages, respectively. The data obtained in the present tests are in harmony with the results of Bell (1976), Barbara et al. (1976), Lindgren and Vincent (1966), How (1973), Bell and Glanville (1973) and El-Lakwah et al. (1991).

High tolerance to phosphine in the egg and pupal stage can be regarded as a common phenomenon, and is undoubtedly linked with metabolism. Phosphine is toxic to insects only in the presence of oxygen (Bond et al., 1967) and stages which can survive without oxygen for a period of time likely to be tolerant. The relationship known as Haber's rule, whereby the level of kill is proportional to the product of concentration and time, fails to apply with phosphine, largely-because in any insect species different stages of development differ widely in tolerance, and development continues during the actual exposure (Reynold et al., 1967 and How, 1973). As can be seen from the results reported here, phosphine was markedly less effective at lower temperature, at which metabolic rate is slower, oxygen consumption is reduced and the development of tolerant immobile stages into more susceptible ones is prolonged.

By comparing the exposure time values required to achieve 100% mortality for the various stages of the tested insects at 26±1°C and 80 vpm phosphine, it can be seen

that the adult stage of all insects was more susceptible to phosphine than the immature stages. The adult stage of C. maculatus was ,however, much more tolerant to phosphine than the adults of both S. oryzae and R. dominica. This phenomenon was much more pronounced at the lower temperature.

The susceptibility of the larvae to phosphine was as the following decreased order: C. maculatus, S. oryzae and R. dominica.

Pupae of C. maculatus were somewhat more tolerant to phosphine than the pupae of both S. oryaze and R. dominica.

Curiously enough to note that the eggs of C. maculatus were much more tolerant to PH_3 than the eggs of R. dominica and S. oryzae at the higher temperature. On the other hand, R. dominica eggs exhibited the highest level of tolernce.

2. Toxicity of carbon dioxide in controlled atmosphere (CA) to the tested insects:

2.1. Efficacy of various CO_2 concentrations in controlled atmosphere (CA) on all stages of S. oryzae:

Tables (10 and 11) represent the data obtained for the different stages of S. oryzae using controlled atmosphere containing various fixed concentrations of CO_2 at 26±1°C and 6±1°C.

Data indicate that the lethal time values required for a certain mortality were generally declined as the CO_2 concentration was increased and ~~these values were shorter at higher temperature than at lower one~~. For example, the lethal time values needed to achieve 90% mortality for the adult stage at 26±1°C using CA containing 12.5, 25, 50, 75 and 100% (v/v) CO_2 were 199, 101, 44, 31 and 19 hr, respectively. The corresponding values at 6±1°C were 289, 199, 142, 82 and 86 hr,

For the larval stage, the lethal exposures to obtain 90% kill were 519, 249, 137, 130 and 117 hr at 26±1°C and 605, 339, 196, 187 and 194 hr at 6±1°C, for the forementioned CO_2 concentrations, respectively.

For the pupal stage, these values were 899, 378, 254, 233 and 207 hr at 26±1°C and 906, 484, 437, 299 and 274 hr at 6±1°C.

Table (10): Lethal time values and slope of regression line for the different stages of *S. oryzae* (L.) exposed to various concentrations of CO_2 in controlled atmosphere at 26±1°C and 60±5% RH.

Atmosphere CO_2 (% v/v)	air	Stage	Lethal times (hr) and their 95% confidence limits				Slope±SE
			LT_{50}	LT_{90}	LT_{99}	$LT_{99.9}$	
12.5	87.5	A	91 (87- 95)	199 (187-213)	380 (336- 431)	696 (514- 723)	3.70±0.50
		L	139 (122-159)	519 (411-656)	1518 (1001-2302)	3323 (1904-5801)	2.24±6.89
		P	187 (162-215)	899 (673-1198)	2411 (1501-3871)	4960 (2624-9164)	2.44±0.12
		E	189 (169-211)	615 (496-764)	1613 (1124-2316)	2263 (2032-5239)	2.50±0.14
25	75	A	42 (40- 44)	101 (95-106)	207 (189- 226)	350 (319- 392)	3.40±1.50
		L	75 (67- 84)	249 (208-298)	666 (485- 913)	1366 (891-2087)	2.45±0.82
		P	100 (87-114)	378 (298-478)	1117 (730-1708)	2467 (1396-4362)	2.22±2.64
		E	104 (94-115)	316 (263-380)	786 (576-1072)	1531 (1018-2301)	2.64±0.16
50	50	A	18 (15- 20)	44 (37- 53)	96 (72- 125)	165 (116- 236)	3.20±1.50
		L	60 (55- 66)	137 (119-157)	268 (213- 338)	439 (323- 959)	3.58±1.83
		P	72 (64- 82)	254 (205-315)	711 (490-1031)	1507 (941-2871)	2.34±0.11
		E	49 (43- 54)	151 (128-176)	381 (293- 495)	750 (530-1061)	2.59±1.03
75	25	A	14 (12- 16)	31 (25- 38)	58 (42- 80)	93 (61- 141)	3.80±0.50
		L	55 (50- 61)	130 (113-149)	261 (207- 330)	436 (319- 596)	3.43±1.49
		P	58 (50- 68)	233 (186-292)	709 (477-1000)	1500 (940-2774)	2.13±0.10
		E	52 (47- 58)	125 (109-144)	257 (204- 323)	435 (320- 590)	3.25±0.82
100	0.0	A	8 (6- 9)	19 (15- 24)	40 (27- 60)	69 (40- 119)	2.20±0.90
		L	52 (47- 58)	117 (103-134)	227 (182- 283)	367 (273- 492)	3.66±1.41
		P	51 (43- 60)	207 (166-259)	654 (431- 991)	1414 (859-2670)	2.09±0.89
		E	42 (38- 47)	95 (84-147)	183 (148- 226)	296 (222- 395)	3.65±1.96

A = Adult, L = Larva, P = Pupa, E = Egg.

Table (11): Lethal time values and slope of regression line for the different stages of *S. oryzae* (L.) exposed to various concentrations of CO_2 in controlled atmosphere at 6±1°C and 60±5% RH.

Atmosphere CO_2	air	Stage	Lethal times (hr) and their 95% confidence limits				Slope±SE
(% v/v)			LT_{50}	LT_{90}	LT_{99}	$LT_{99.9}$	
12.5	87.5	A	179 (171-188)	289 (264-317)	428 (370- 496)	571 (472- 689)	6.13±0.45
		L	201 (181-224)	605 (495-739)	1783 (1069-2057)	3856 (1866-4371)	2.68±0.10
		P	268 (235-304)	906 (643-1255)	3229 (1812-5755)	8224 (3843-17600)	1.88±0.13
		E	248 (220-380)	873 (672-1135)	2435 (1590-3730)	5151 (2969-8939)	2.35±0.18
25	75	A	108 (100-117)	199 (172-230)	329 (262- 413)	475 (355- 636)	4.79±4.10)
		L	129 (117-143)	339 (286-401)	742 (551-1000)	1398 (885-1962)	3.07±0.47
		P	187 (169-206)	484 (399-586)	1617 (1019-2566)	2655 (2271-7791)	2.79±0.35
		E	148 (134-164)	424 (348-515)	998 (724-1375)	1867 (1230-2832)	2.81±5.81
50	50	A	55 (49- 62)	142 (113-177)	308 (212- 447)	543 (333- 883)	3.10±0.34
		L	78 (71- 85)	196 (169-226)	560 (428- 625)	718 (527- 979)	3.20±1.93
		P	88 (76-102)	437 (337-567)	1152 (830-1710)	2277 (2061-6703)	1.84±0.12
		E	80 (71- 91)	297 (236-375)	871 (584-1301)	1911 (1123-3254)	2.24±0.50
75	25	A	45 (42- 49)	82 (74- 91)	134 (114- 158)	192 (156- 238)	4.89±0.82
		L	73 (66- 80)	187 (162-216)	547 (367- 598)	704 (652- 970)	3.14±1.74
		P	71 (61- 82)	299 (233-384)	968 (620-1513)	2283 (1255-4152)	2.05±4.57
		E	64 (58- 71)	192 (153-241)	511 (342- 764)	1044 (610-1788)	2.46±0.31
100	0.0	A	42 (38- 47)	86 (73- 98)	152 (119- 193)	231 (168- 318)	4.19±0.21
		L	54 (46- 63)	194 (152-245)	402 (355- 509)	669 (515- 926)	2.32±0.12
		P	60 (51- 71)	274 (212-354)	942 (589-1507)	1623 (1229-4390)	1.95±7.51
		E	58 (50- 67)	176 (152-205)	401 (311- 517)	733 (523-1026)	2.92±1.77

A = Adult, L = Larva, P = Pupa, E = Egg.

Table (12): Lethal time values and slope of regression line for the different stages of *R. dominica* (Fab) exposed to various concentrations of CO_2 in controlled atmosphere at 26±1°C and 60±5% RH.

Atmosphere CO_2 (% v/v)	Atmosphere air (% v/v)	Stage	Lethal times (hr) and their 95% confidence limits LT_{50}	LT_{90}	LT_{99}	$LT_{99.9}$	Slope±SE
12.5	87.5	A	72 (68- 75)	231 (211-253)	604 (517- 706)	1219 (992-1498)	2.51±0.08
		L	110 (95-128)	395 (319-488)	1114 (751-1654)	2044 (1413-2956)	2.32±7.62
		P	183 (153-217)	919 (624-1359)	2430 (1697-6930)	4979 (3502-23021)	1.83±0.11
		E	167 (145-191)	733 (548-982)	1455 (1371-4099)	3938 (3008-11721)	2.36±0.12
25	75	A	54 (48- 60)	122 (108-139)	241 (193- 299)	394 (294- 528)	3.56±1.11
		L	65 (57- 74)	241 (199-291)	705 (498-1000)	1446 (965-2167)	2.24±0.80
		P	115 (100-131)	467 (358-609)	1467 (918-2345)	3388 (1816-6323)	2.10±2.59
		E	113 (104-123)	274 (238-316)	566 (448- 716)	962 (707-1309)	3.32±0.36
50	50	A	20 (17- 22)	44 (37- 51)	84 (65- 108)	136 (98- 187)	3.67±0.57
		L	45 (37- 54)	171 (148-197)	385 (301- 492)	698 (503- 968)	2.96±1.51
		P	69 (59- 80)	312 (238-408)	1069 (656-1740)	2630 (1367-5059)	1.95±0.18
		E	70 (63- 77)	173 (150-199)	363 (287- 460)	626 (458- 657)	3.23±0.49
75	25	A	14 (12- 16)	28 (22- 35)	48 (34- 68)	71 (46- 111)	4.42±0.06
		L	45 (40- 52)	131 (113-153)	314 (240- 410)	593 (411- 855)	2.96±0.84
		P	56 (48- 67)	255 (198-328)	830 (544-1389)	2134 (1130-4028)	1.96±0.19
		E	56 (50- 62)	141 (123-162)	300 (238- 378)	521 (383- 709)	3.19±0.84
100	0.0	A	13 (11- 15)	23 (17- 30)	36 (24- 55)	51 (30- 88)	5.15±0.18
		L	33 (29- 38)	106 (90-125)	252 (197- 324)	436 (311- 612)	2.56±1.33
		P	49 (43- 55)	140 (121-163)	333 (255- 435)	626 (436- 900)	2.79±1.16
		E	47 (42- 53)	114 (101-129)	235 (191- 290)	398 (300- 528)	3.34±1.07

A = Adult, L = Larva, P = Pupa, E = Egg.

Table (13): Lethal time values and slope of regression line for the different stages of R. dominica (Fab) exposed to various concentrations of CO_2 in controlled atmosphere at 6±1°C and 60±5% RH.

Atmosphere CO_2 (% v/v)	air	Stage	Lethal times (hr) and their 95% confidence limits LT_{50}	LT_{90}	LT_{99}	$LT_{99.9}$	Slope±SE
12.5	87.5	A	147 (140-153)	235 (209-261)	319 (284- 359)	412 (354- 481)	6.86±0.96
		L	187 (169-206)	503 (423-599)	1131 (852-1501)	2380 (1391-4071)	2.98±0.16
		P	230 (199-266)	987 (680-1417)	3631 (1732-6027)	7691 (3387-17460)	2.03±0.20
		E	212 (188-238)	748 (585-957)	2095 (1391-3157)	4446 (2625-7588)	2.34±0.13
25	75	A	84 (77- 92)	181 (157-210)	342 (272- 429)	543 (405- 727)	3.80±3.55
		L	137 (124-151)	363 (305-433)	807 (595-1095)	1547 (964-2481)	3.02±0.27
		P	164 (147-184)	554 (432-710)	1493 (994-2241)	4479 (1819-5212)	2.43±4.39
		E	138 (123-156)	407 (327-506)	981 (671-1434)	1868 (1129-3092)	2.73±0.13
50	50	A	44 (40- 49)	96 (82-112)	181 (143- 228)	288 (214- 387)	3.79±2.10
		L	63 (57- 70)	188 (150-235)	610 (393- 946)	1441 (782-2655)	2.04±0.50
		P	91 (79-105)	450 (345-587)	1657 (1040-2641)	4298 (2310-7985)	1.85±3.69
		E	97 (87-110)	332 (265-416)	910 (624-1326)	1900 (1159-3114)	2.39±1.14
75	25	A	46 (42- 49)	75 (67- 83)	112 (95- 131)	150 (122- 184)	5.95±0.92
		L	57 (51- 64)	157 (136-181)	357 (279- 456)	650 (467- 906)	2.93±1.19
		P	83 (72- 96)	380 (284-509)	1313 (787-2188)	3246 (1648-6393)	1.94±0.12
		E	62 (54- 70)	207 (170-251)	554 (394- 779)	1141 (723-1802)	2.44±8.51
100	0.0	A	39 (37- 43)	86 (74-100)	162 (128- 205)	259 (192- 350)	3.76±1.42
		L	48 (42- 54)	119 (103-138)	272 (208- 357)	542 (377- 779)	3.21±1.32
		P	68 (59- 79)	307 (235-401)	1049 (649-1695)	2571 (1349-49010)	1.96±0.11
		E	54 (47- 63)	180 (145-223)	479 (324- 706)	980 (579-1657)	2.46±3.91

A = Adult, L = Larva, P = Pupa, E = Egg.

Results indicate that the lethal time values needed to obtain 90% kill for the adults at 26±1°C using CA containing 12.5, 25, 50, 75 and 100% (v/v) CO_2 were 231, 122, 44, 28 and 23 hr, respectively. The corresponding values at 6±1°C were 235, 181, 96, 75 and 86 hr,

For the larval stage, the lethal exposure values required to obtain 90% mortality were 395, 241, 171, 131 and 106 hr at 26±1°C and 503, 363, 188, 157 and 119 hr at 6±1°C.

For the pupal stage these values were 919, 467, 312, 255 and 140 hr at 26±1°C and 987, 554, 450, 380 and 307 hr for the forementioned CO_2 concentrations, respectively.

The corresponding values for the egg stage were 733, 274, 173, 141 and 114 hr at 26±1°C and 748, 407, 332, 207 and 180 hr at 6±1°C.

It is obvious, that these values were shorter at higher temperature than those at lower temperature.

Data recorded at 6±1°C for the adult stage revealed that the effectiveness of 100% (v/v) CO_2 in controlled atmosphere was lower than that of 75% (v/v) CO_2 and that could be due to nearly complete depletion of oxygen in the CA containing 100% (v/v) CO_2.

Generally, the higher the concentration of CO_2 in the CA was, the lethal time values were accordingly decreased.

Data show also that at 26±1°C and 6±1°C the adult stage of R. dominica was the most susceptible stage to CA containing CO_2 followed by larva, egg and pupae, when the results compared at the LT_{90} level.

2.3. Efficacy of various CO_2 concentrations in CA against the different stages of C. maculatus:

The lethal time values and slope of regression line for all stages of C. maculatus exposed to various concentrations of CO_2 in controlled atmosphere at 26±1°C and 6±1°C are shown in Tables (14 and 15).

Data indicate that the lethal time values needed to obtain 90% kill for the adults at 26±1°C using CA with 12.5, 25, 50, 75 and 100% (v/v) CO_2 were 140, 76, 57, 35 and 22 hr, respectively. The corresponding values at 6±1°C were 150, 171, 151, 86 and 118 hr,

For the larval stage, the lethal exposure values to achieve 90% mortality were 578, 386, 164, 140 and 137 hr at 26±1°C and 807, 451, 299, 234 and 211 hr at 6±1°C for the forementioned CO_2 concentrations, respectively.

Table (14): Lethal time values and slope of regression line for the different stages of *C. maculatus* (F.) exposed to various concentrations of CO_2 in controlled atmosphere at 26±1°C and 60±5% RH.

Atmosphere CO_2 (% v/v)	air	Stage	Lethal times (hr) and their 95% confidence limits				Slope±SE
			LT_{50}	LT_{90}	LT_{99}	$LT_{99.9}$	
12.5	87.5	A	84 (82- 86)	140 (135-146)	214 (200- 228)	291 (267- 316)	5.72±0.89
		L	198 (178-219)	578 (472-708)	1386 (996-1929)	2627 (1712-4032)	2.75±0.22
		P	211 (189-234)	560 (457-686)	1599 (916-2721)	3877 (1871-8036)	3.02±0.28
		E	240 (218-265)	651 (535-792)	1466 (1073-2002)	2653 (1779-3958)	2.96±0.78
25	75	A	33 (29- 37)	76 (67- 88)	153 (123- 190)	254 (191- 337)	3.47±0.95
		L	111 (100-124)	386 (305-489)	1072 (727-1581)	2261 (1365-3743)	2.36±1.19
		P	102 (88-118)	462 (342-624)	1241 (889-1732)	2221 (1440-3425)	1.96±0.59
		E	70 (61- 81)	301 (238-380)	994 (650-1520)	2280 (1343-4216)	2.02±0.17
50	50	A	18 (15- 20)	57 (48- 67)	148 (113- 195)	300 (208- 431)	2.50±1.11
		L	60 (52- 65)	164 (141-190)	381 (295- 492)	706 (501- 996)	2.85±1.47
		P	97 (87-109)	323 (256-408)	860 (587-1260)	1759 (1072-1260)	2.46±1.23
		E	44 (37- 52)	185 (159-217)	424 (324- 555)	775 (541-1112)	2.91±0.36
75	25	A	13 (11- 16)	35 (29- 43)	78 (57- 108)	141 (92- 216)	3.01±0.53
		L	58 (54- 65)	140 (124-158)	293 (157- 232)	510 (373- 695)	3.43±1.79
		P	75 (66- 84)	256 (206-317)	699 (483-1010)	1457 (894-2374)	2.39±1.07
		E	43 (38- 48)	108 (94-124)	231 (181- 295)	401 (288- 560)	3.17±0.39
100	0.0	A	11 (9- 12)	22 (18- 27)	39 (28- 54)	60 (40- 91)	4.06±0.48
		L	54 (48- 60)	137 (120-157)	283 (231- 347)	472 (360- 620)	3.17±0.71
		P	63 (57- 71)	181 (155-213)	428 (325- 562)	800 (556-1152)	2.08±2.25
		E	30 (26- 35)	70 (61- 81)	140 (110- 178)	232 (167- 321)	3.49±0.37

A = Adult, L = Larva, P = Pupa, E = Egg.

Table (15): Lethal time values and slope of regression line for the different stages of *C. maculatus* (F.) exposed to various concentrations of CO_2 in controlled atmosphere at 6±1°C and 60±5% RH.

Atmosphere CO_2 (% v/v)	air	Stage	Lethal times (hr) and their 95% confidence limits LT_{50}	LT_{90}	LT_{99}	$LT_{99.9}$	Slope±SE
12.5	87.5	A	118 (113-124)	150 (140-161)	183 (164- 204)	211 (183- 243)	12.30±2.73
		L	239 (212-269)	807 (623-1045)	2179 (1439-3301)	4504 (2640-7684)	2.42±0.34
		P	283 (249-320)	1036 (674-1593)	4830 (2272-9835)	14876 (5919-37385)	2.81±2.25
		E	284 (255-315)	799 (643-992)	1858 (1323-2609)	3443 (2233-5309)	2.85±0.46
25	75	A	76 (69- 83)	171 (147-199)	331 (261- 421)	538 (395- 734)	3.63±0.12
		L	143 (134-151)	451 (326-626)	1399 (1201-2100)	2648 (1125-6233)	5.20±0.85
		P	210 (188-235)	910 (685-1208)	2363 (1494-3736)	4744 (2627-8564)	2.52±0.20
		E	113 (97-130)	377 (299-477)	1013 (659-1556)	2083 (1064-3728)	2.44±0.13
50	50	A	53 (47- 60)	151 (119-193)	361 (247- 527)	680 (419-1104)	2.77±1.02
		L	88 (80- 96)	299 (210-427)	1054 (556-2001)	2548 (1125-6123)	1.91±0.75
		P	157 (133-184)	606 (478-768)	1437 (994-2077)	2701 (1692-4310)	2.79±0.35
		E	68 (61- 76)	186 (159-217)	460 (320- 661)	969 (601-1649)	2.28±0.13
75	25	A	49 (45- 52)	86 (77- 95)	137 (117- 160)	192 (157- 236)	5.16±1.78
		L	77 (70- 86)	234 (199-276)	522 (400- 684)	941 (663-1333)	3.00±3.19
		P	115 (102-131)	385 (290-510)	1026 (633-1662)	2102 (1115-3962)	2.45±0.25
		E	68 (61- 75)	185 (158-218)	424 (324- 555)	774 (540-1107)	2.92±0.24
100	0.0	A	44 (39- 49)	118 (96-146)	268 (192- 375)	488 (317- 753)	2.94±1.23
		L	65 (54- 75)	211 (180-248)	480 (369- 626)	874 (618-1237)	2.94±2.58
		P	75 (67- 84)	248 (202-303)	656 (465- 926)	1337 (848-2110)	2.74±0.32
		E	48 (40- 56)	165 (133-206)	417 (305- 684)	759 (552-1665)	2.34±3.82

A = Adult, L = Larva, P = Pupa, E = Egg.

The values of the pupae were 560, 462, 323, 256 and 181 hr at 26±1°C and 1036, 910, 606, 385 and 248 hr at 6±1°C. The corresponding values for the eggs were 651, 301, 185, 108 and 70 hr at 26±1°C and 799, 377, 186, 185 and 165 hr,

Results show clearly that the lethal time values were longer at lower temperature than at higher one. At 26±1°C the higher the concentration of CO_2 in the CA was, the mortality of the various stages of C. maculatus was accordingly increased and the lethal exposure values were declined.

The same trend was observed at 6±1°C for the immature stages, and the mortality of the adult stage was increased by rising the CO_2 concentration from 25% to 75% in the CA. By using CA containing 100% (v/v) CO_2 at the lower temperature the lethal time values achieved to kill the adults of C. maculatus were obvious longer than those obtained for the CA containing 75% (v/v) CO_2. This result is similar to those obtained with the adult stages of S. oryzae and R. dominica. This result is in agreement with the findings of Lindgren and Vincent (1970), Reichmuth (1986), Krishnamurthy et al. (1986) and Tunc (1983).

By comparing the susceptibility of the different stages of C. maculatus at the LT_{90}-level, it was found that, at 26±1°C, the order of tolerance to atmosphere containing

25, 75 and 100% CO_2 (v/v) was pupa > larva > egg > adult. With 12.5% CO_2 the order of tolerance was egg > larva > pupa > adult, and it was pupa > larva > egg > adult for an atmosphere containig 50% (v/v) CO_2. At 6±1°C the order of tolerance to the various CO_2 concentrations and at the LT_{90} level was pupae > larva > egg > adult.

Lindgren and Vincent (1970) mentioned that S. granarius adults were the most susceptible stage to atmospheres of CO_2, N_2 or He, followed by larvae, pupae and eggs. S. oryzae adults were the most susceptible stage to atmospheres of CO_2, N_2 or He, followed by larvae, eggs, and pupae. CO_2 concentrations of 90-40% in air were more toxic to S. oryzae adults than 100% CO_2. Concentrations of 90-60% CO_2 in air were more toxic to S. granarius adults than 100% CO_2.

Storey (1978) reported that at 27°C, times of exposure for 100% mortality were 48 hr for adults of C. maculatus F., 96 hr for 1 and 3 day-old eggs, 120 hr for 7 and 14-day old larvae and 192 hr for 21-day-old larvae and pupae.

Calderon and Navarro (1979) found that efficacy of CO_2 treatment decreases as the O_2 concentration approaches the level of a normal atmosphere.

Childs and Overby (1983) mentioned that overall, an atmosphere of 65% CO_2 was more toxic to eggs, larvae, pupae,

and adults of Lasioderma serricorne (F.) than an atmosphere of 35 or 92% CO_2. The pupal stage tolerated CO_2 the best, some pupae surviving exposure of 7 days. Other stages, in increasing order of CO_2 susceptibility, were larvae, adult, and egg.

The results obtained could be summarized as follow:

Tests carried out to study the effectiveness of various fixed CO_2 concentrations in controlled atmosphere, against the different stages of S. oryzae, R. dominca and C. maculatus showed that carbon dioxide was more effective at higher temperature than at lower one. Mortility was increased generally as the concentration of CO_2 was increased. The lethal time values recorded for the adults at the lower temperature (6±1°C) with CA containing 100% (v/v) CO_2 were higher than those achieved with CA containing 75% (v/v) CO_2, and this result could be due to nearly total depletion of oxygen in the controlled atmosphere containing 100% (v/v) CO_2. The adults of the insects were the most susceptible stage and the pupae were the most tolerant stage at the two test temperatures.

3. Toxicity of mixtures of phosphine plus carbon dioxide to the tested insects:

3.1. Efficacy of phosphine alone and in mixtures with carbon dioxide against the various stages of S. oryzae:

Tables (16 and 17) show the lethal time values, slope of regression line and categories of joint action for the various stages of S. oryzae, exposed to phosphine alone (20 vpm in air) and to mixtures of phosphine + 25 and 50% CO_2 at 26±1°C and 6±1°C.

Data indicate that time to mortality was generally reduced in the presence of carbon dioxide at the two test temperatures. For example the lethal time values required to obtain 90% adult mortality at 26±1°C (see Fig., 4) fell from 17 hr in air containing only 20 vpm PH_3 to 13 hr as well as to 11 hr in the presence of 25 and 50% CO_2, respectively. For the larval stage time to 90% mortality was reduced from 51 hr in phosphine alone to 31 hr as well as to 29 hr in the mixtures of PH_3 + CO_2. The same trend was also obtained for the pupal and egg stages.

At 6±1°C (Table, 17 and Fig. 5) the lethal time values required to achieve 90% mortality for the various stages of S. oryzae were (119, 162, 141 and 261 hr) with 20 vpm PH_3 alone, (50, 58, 87 and 102 hr) with 20 vpm PH_3 + 25% CO_2, and (41, 49, 99 and 106 hr) with mixture contained 20 vpm + 50% CO_2 for the adult, larval, pupal and egg stage, respectively. These values were greater than those obtained at higher temperature.

Table (16): Lethal time values (LT_{50}, LT_{90} and LT_{99}), slope of regression line and categories of joint action for S. oryzae exposed to phosphine alone and to mixtures of phosphine + CO_2 at 26±1°C.

Treatment	Stage	Lethal times (hr), their 95% confidence limits and categories of joint action						
		LT_{50}	C	LT_{90}	C	LT_{99}	C	Slope ± SE
20 vpm PH_3 alone	Adult	10 (9-10)	-	17 (15-19)	-	27 (22-33)	-	3.23±2.00
	Larva	9 (8-11)	-	51 (38-69)		209 (125-350)	-	1.84±0.40
	Pupa	13 (11-15)	-	51 (40-64)	-	157 (107-232)	-	2.09±0.32
	Egg	38 (34-44)	-	122 (101-146)	-	313 (234-419)	-	1.54±1.83
20 vpm PH_3 + 25% v/v CO_2	Adult	5 (4- 5)	s	13 (11-17)	s	32 (22-46)	i	2.78±0.92
	Larvae	8 (7- 9)	s	31 (25-37)	s	90 (65-124)	s	2.23±1.28
	Pupa	11 (9-12)	s	39 (32-47)	i	367 (244-553)	i	1.54±0.30
	Egg	11 (9-14)	s	77 (60-98)	i	317 (203-513)	a	1.54±0.30
20 vpm PH_3 + 50% v/v CO_2	Adult	3 (2- 4)	s	11 (9-14)	s	26 (21-40)	s	2.23±2.73
	Larva	7 (6-10)	s	29 (23-35)	s	74 (54-102)	s	2.53±0.96
	Pupa	9 (8-11)	i	43 (36-53)	i	156 (114-214)	i	1.88±1.06
	Egg	10 (8-12)	s	61 (48-77)	i	265 (180-393)	a	1.63±0.54

a = antagonistic effect.
c = category of joint action.
i = independent joint action (additive effect)
s = synergistic effect.

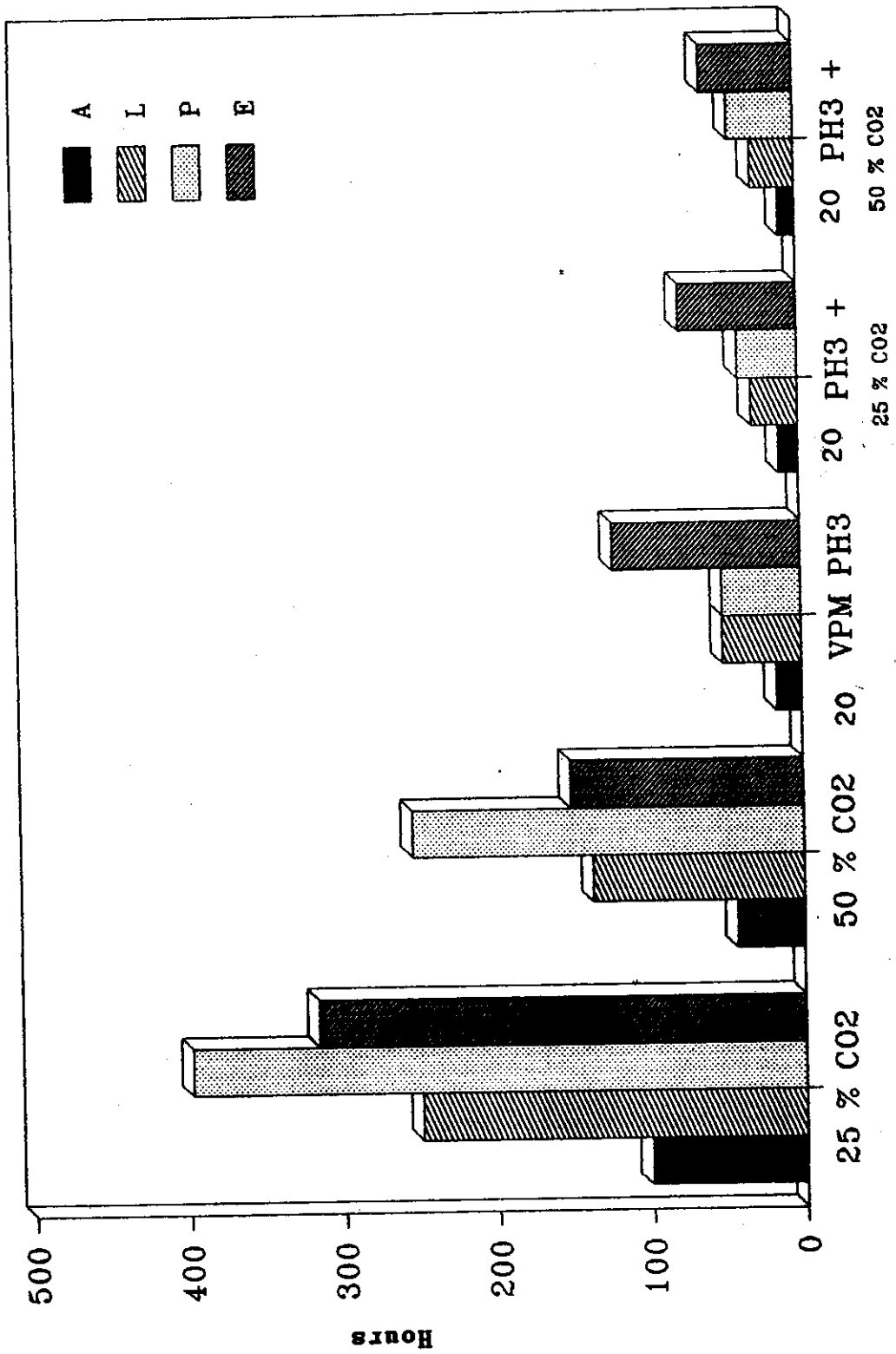

Fig. (4) : Time to 90 % mortality for the different stages of *S. oryzae* (L) with 25 and 50 % CO_2, 20 VPM PH_3 alone, and Mixtures of 20 VPM PH_3 + 25 and 50 % CO_2 at 26±1 °C.

Table (17): Lethal time values (LT_{50}, LT_{90} and LT_{99}), slope of regression line and categories of joint action for S. oryzae exposed to phosphine alone and to mixtures of phosphine + CO_2 at 6±1°C.

Treatment	Stage	Lethal times (hr), their 95% confidence limits and categories of joint action						
		LT_{50}	C	LT_{90}	C	LT_{99}	C	Slope ± SE
20 vpm PH_3 alone	Adult	25 (21-29)	–	119 (88-160)	–	431 (271-688)	–	1.87±0.35
	Larva	20 (17-25)	–	162 (111-236)	–	489 (462-1712)	–	1.41±0.30
	Pupa	23 (19-27)	–	141 (102-195)	–	623 (362-1071)	–	1.62±0.46
	Egg	49 (42-57)	–	261 (197-345)	–	1029 (642-1649)	–	1.75±0.39
20 vpm PH_3 + 25% v/v CO_2	Adult	14 (12-17)	s	50 (41- 61)	s	137 (98-190)	s	2.38±1.49
	Larva	12 (10-14)	s	58 (47- 71)	s	208 (148-292)	s	1.88±1.52
	Pupa	14 (12-17)	s	87 (68-112)	s	378 (246-580)	i	1.64±0.48
	Egg	11 (9-14)	s	102 (75-137)	i	610 (351-1061)	a	1.34±0.11
20 vpm PH_3 + 50% v/v CO_2	Adult	11 (9-13)	s	41 (34- 50)	s	120 (87-166)	s	2.24±1.10
	Larva	6 (5- 8)	s	49 (37- 63)	s	252 (159-398)	s	1.46±2.16
	Pupa	16 (13-19)	i	99 (77-128)	a	450 (288-701)	a	1.59±0.31
	Egg	18 (15-21)	s	106 (82-137)	i	452 (294-694)	a	1.66±0.40

a = antagonistic effect.
c = category of joint action.
i = independent joint action (additive effect)
s = synergistic effect.

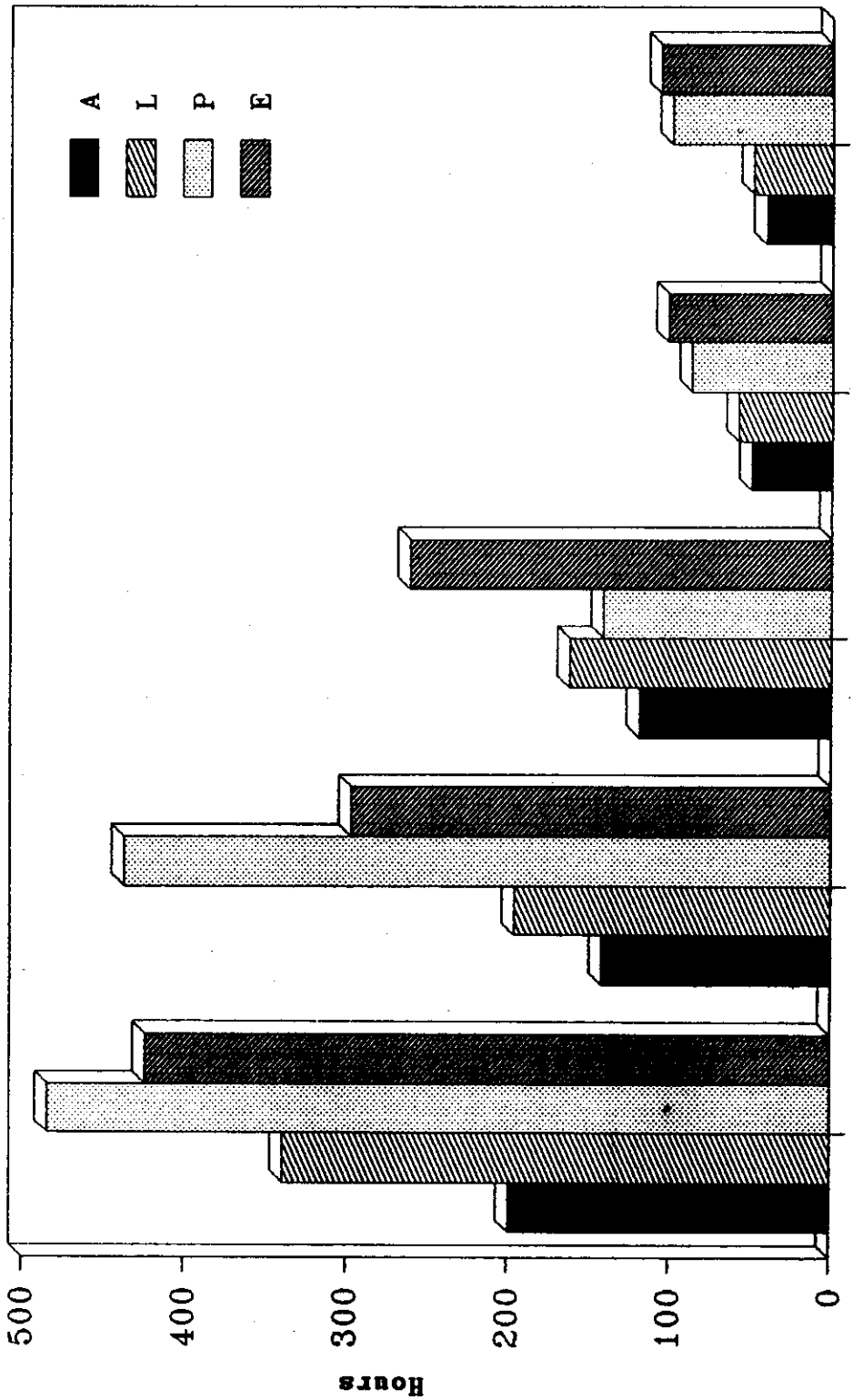

Fig. (5) : Time to 90 % mortality for the different stages of *S. oryzae* (L) with 25 and 50 % CO_2, 20 VPM PH_3 alone, and Mixtures of 20 VPM PH_3 + 25 and 50 % CO_2 at 6±1 °C.

Tables (18 and 19) demonstrate the lethal time values, slope of regression line and categories of joint action for the different stages of S. oryzae exposed to 40 vpm phosphine and to mixtures of 40 vpm PH_3 + 25% and 50% CO_2 at 26±1°C and 6±1°C.

Results show (see also Fig., 6) that the lethal time values obtained to cause 90% kill were decreased by the addition of CO_2 to phosphine in the mixtures. For example the lethal exposure values caused 90% mortality for the various stages at 26±1°C were (16, 23, 44 and 90 hr) with 40 vpm phosphine alone, (6, 14, 51 and 31 hr) with the mixture of 40 vpm PH_3 + 25% CO_2 and (9, 20, 37 and 28 hr) with the mixture contained 40 vpm PH_3 + 50% CO_2 for the adult, larval, pupal and egg stages respectively.

The corresponding values at 6±1°C (Table, 19 and Fig., 7) were (34, 88, 85 and 223 hr) with 40 vpm phosphine alone, (29, 48, 71 and 52 hr) with the mixture of 40 vpm PH_3 + 25% CO_2 and (11, 31, 48 and 66 hr) with the mixture of 40 vpm PH_3 + 50% CO_2 for the forementioned various stages of S. oryzae, respectively.

Results revealed also that time to mortilities were shorter at higher temperature than at lower one and the adult stage was the most susceptible stage to phosphine as well as to mixtures of PH_3 + CO_2 at the two test temperatures.

Table (18): Lethal time values (LT_{50}, LT_{90} and LT_{99}), slope of regression line and categories of joint action for S. oryzae exposed to phosphine alone and to mixtures of phosphine + CO_2 at 26±1°C.

Treatment	Stage	Lethal times (hr), their 95% confidence limits and categories of joint action						
		LT_{50}	C	LT_{90}	C	LT_{99}	C	Slope ± SE
40 vpm PH_3 alone	Adult	6 (5- 7)	-	16 (13-19)	-	34 (24- 48)	-	3.10±0.51
	Larva	8 (7- 9)	-	23 (19-27)	-	54 (41- 71)	-	2.80±0.95
	Pupa	16 (14-18)	-	44 (36-53)	-	101 (76-135)	-	2.90±1.15
	Egg	26 (22-31)	-	90 (69-118)	-	249 (162-383)	-	2.37±0.02
40 vpm PH_3 + 25% v/v CO_2	Adult	2 (2- 3)	s	6 (5- 8)	s	12 (9- 18)	s	3.21±1.81
	Larva	5 (4- 6)	s	14 (11-17)	s	30 (21- 44)	s	3.02±0.48
	Pupa	12 (10-14)	i	51 (41-63)	i	164 (117-230)	a	2.06±0.42
	Egg	8 (7- 9)	s	31 (26-38)	s	94 (69-128)	s	2.19±0.34
40 vpm PH_3 + 50% v/v CO_2	Adult	3 (2- 3)	s	9 (7-11)	s	24 (16- 35)	s	2.39±0.32
	Larva	6 (6- 7)	s	20 (16-25)	s	52 (36- 75)	s	2.57±0.99
	Pupa	6 (6- 9)	i	37 (30-46)	i	137 (98-191)	a	1.85±0.62
	Egg	8 (7- 9)	s	28 (23-35)	s	82 (60-112)	s	2.26±0.59

a = antagonistic effect.
c = category of joint action.
i = independent joint action (additive effect)
s = synergistic effect.

Table (19): Lethal time values (LT_{50}, LT_{90} and LT_{99}), slope of regression line and categories of joint action for S. oryzae exposed to phosphine alone and to mixtures of phosphine + CO_2 at 6±1°C.

Treatment	Stage	Lethal times (hr), their 95% confidence limits and categories of joint action						
		LT_{50}	C	LT_{90}	C	LT_{99}	C	Slope ± SE
40 vpm PH_3 alone	Adult	11 (10-13)	-	34 (29-100)	-	82 (64-105)	-	2.71±2.30
	Larva	16 (12-22)	-	88 (68-114)	-	348 (203-596)	-	1.75±0.78
	Pupa	11 (8-13)	-	85 (61-119)	-	476 (257-884)	-	1.39±0.20
	Egg	37 (31-44)	-	223 (155-320)	-	974 (538-1761)	-	1.63±0.34
40 vpm PH_3 + 25% v/v CO_2	Adult	7 (6- 8)	s	29 (24- 36)	s	94 (66-133)	s	2.07±1.06
	Larva	10 (9-12)	s	48 (40- 59)	s	172 (123-243)	s	1.69±0.12
	Pupa	18 (15-21)	i	91 (71-116)	i	345 (226-529)	i	1.80±0.15
	Egg	12 (9-14)	s	53 (43- 64)	i	182 (127-259)	i	1.94±1.18
40 vpm PH_3 + 50% v/v CO_2	Adult	3 (3- 4)	s	11 (9- 13)	s	26 (19- 36)	s	2.68±1.48
	Larva	6 (5- 7)	s	31 (25- 39)	s	124 (85-182)	s	1.73±1.00
	Pupa	12 (10-13)	i	48 (40- 58)	i	154 (115-205)	i	2.07±0.81
	Egg	11 (9-13)	s	66 (52-83)	i	290 (191-340)	i	1.62±0.98

a = antagonistic effect.
c = category of joint action.
i = independent joint action (additive effect)
s = synergistic effect.

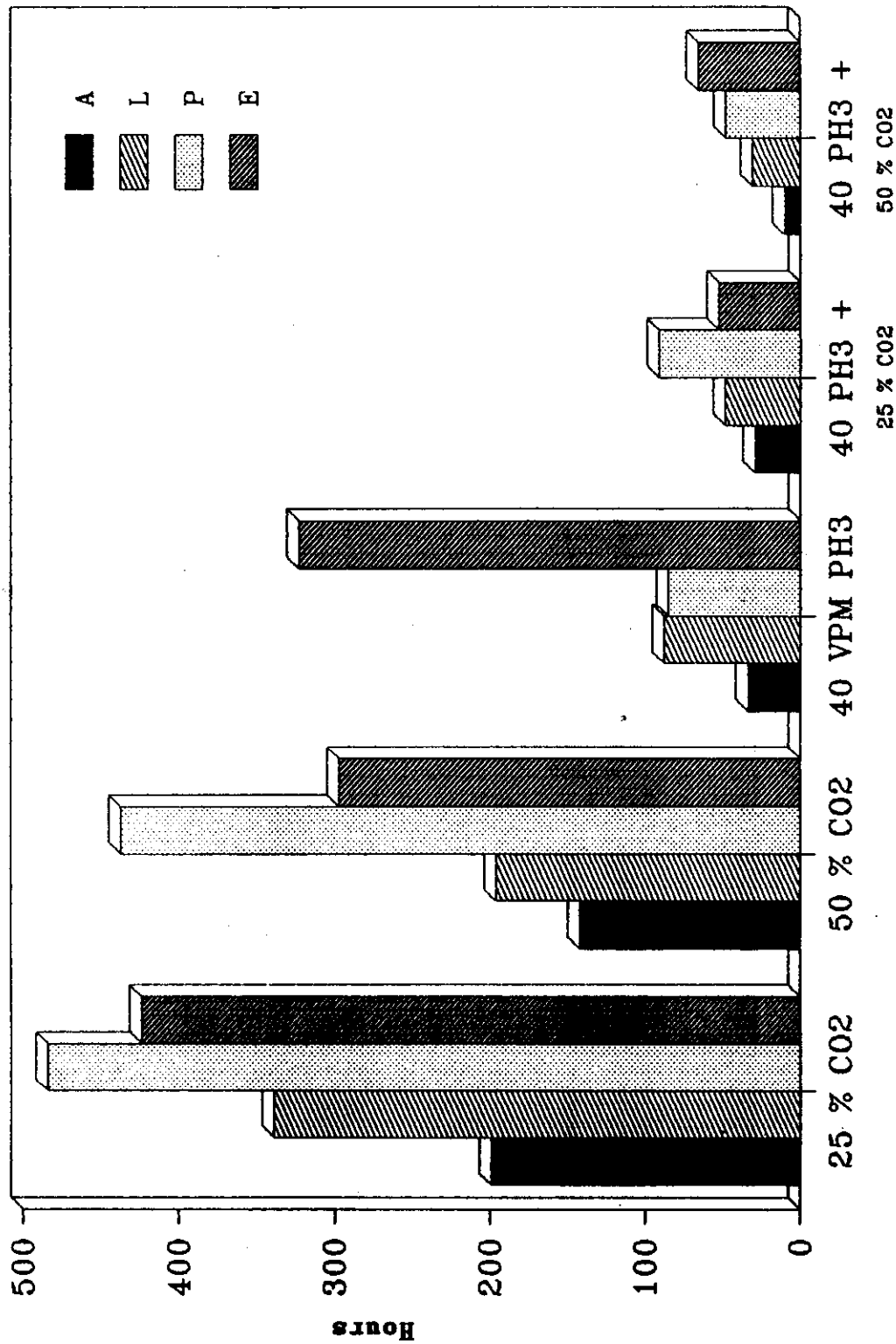

Fig. (7) : Time to 90 % mortality for the different stages of *S. oryzae* (L) with 25 and 50 % CO_2, 40 VPM PH_3 alone, and Mixtures of 40 VPM PH_3 + 25 and 50 % CO_2 at 26±1 °C.

Results obtained at 26±1°C and 6±1°C revealed that a synergistic action was proved at the LT_{90} level with the mixtures of phosphine + carbon dioxide for the adult and larval stages.

For the pupal stage, an independent joint action was obtained with the mixtures at the higher temperature. At 6±1°C, a synergistic effect by 20 vpm PH_3 + 25% CO_2, an independent joint action by addition of 25 and 50% CO_2 to 40 vpm PH_3, and an antagonistic effect with mixture contained 20 vpm PH_3 + 50% CO_2, were proved for the pupal stage of S. oryzae.

For the eggs, a synergistic action by addition of 25 and 50% CO_2 to 40 vpm PH_3, an additive effect with mixtures of 20 vpm PH_3 + 25% CO_2 and 20 vpm PH_3 + 50% CO_2, were observed at 26±1°C. At the lower temperature, an independent joint action (additive effect) was achieved for the eggs of S. oryzae with all mixtures of phosphine + carbon dioxide.

3.2. Efficacy of phosphine alone and in mixtures with carbon dioxide against the various stages of R. dominica:

Tables (20 and 21) demonstrate the lethal time values, slope of regression line and categories of joint action for the various stages of R. dominica, exposed to phosphine alone (20 vpm PH_3 in air) and to mixtures of PH_3 + 25 and 50% CO_2 at 26±1°C and 6±1°C.

Table (20): Lethal time values (LT_{50}, LT_{90} and LT_{99}), slope of regression line and categories of joint action for R. dominica (F.) exposed to phosphine alone and to mixtures of phosphine + CO_2 at 26±1°C.

Treatment	Stage	Lethal times (hr), their 95% confidence limits and categories of joint action						
		LT_{50}	C	LT_{90}	C	LT_{99}	C	Slope ± SE
20 vpm PH_3 alone	Adult	8 (8- 9)	-	16 (14-18)	-	28 (23- 34)	-	4.35±0.51
	Larva	16 (14-18)	-	44 (37-52)	-	101 (77-133)	-	2.86±1.66
	Pupa	47 (41-54)	-	133 (105-168)	-	311 (212-458)	-	2.82±0.06
	Egg	38 (32-45)	-	133 (101-174)	-	369 (233-583)	-	2.36±0.08
20 vpm PH_3 + 25% v/v CO_2	Adult	1 (0- 2)	s	4 (3- 6)	s	17 (8- 35)	s	1.65±0.26
	Larva	9 (7-10)	s	35 (29-43)	i	92 (78-153)	i	2.13±0.80
	Pupa	10 (7-12)	s	70 (54-91)	i	361 (224-581)	a	1.47±0.68
	Egg	12 (10-14)	s	62 (51-75)	s	237 (172-326)	i	1.79±2.36
20 vpm PH_3 + 50% v/v CO_2	Adult	3 (3- 4)	s	7 (6- 9)	s	14 (10- 19)	s	3.58±0.69
	Larva	9 (8-11)	s	37 (31-45)	i	119 (86-165)	i	2.08±0.56
	Pupa	10 (8-12)	s	69 (54-88)	a	346 (227-526)	a	1.49±0.47
	Egg	9 (8- 11)	s	37 (31-45)	s	116 (87-155)	s	2.13±0.66

a = antagonistic effect.
c = category of joint action.
i = independent joint action (additive effect)
s = synergistic effect.

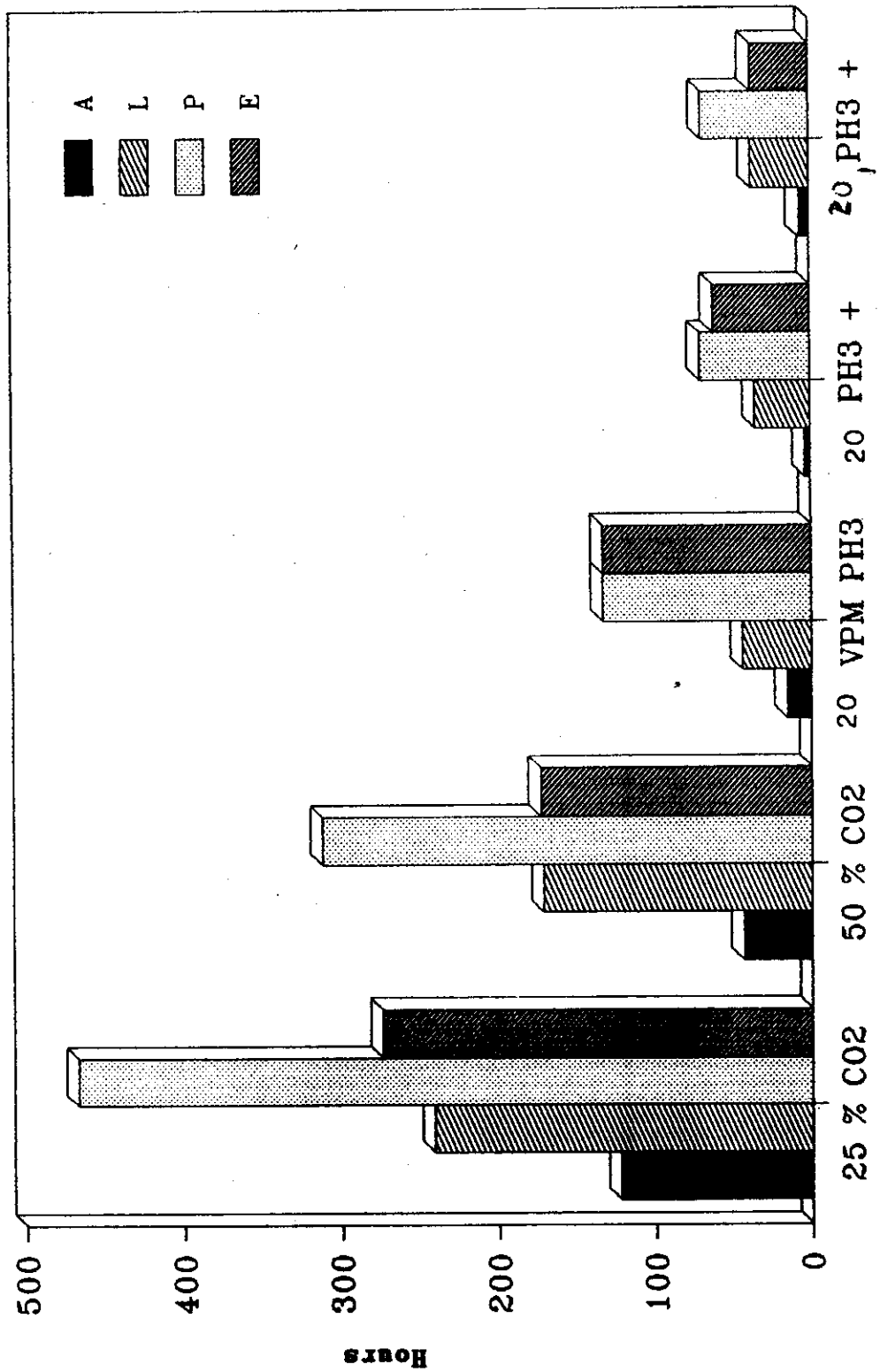

Fig. (8) : Time to 90 % mortality for the different stages of R. dominica (F) with 25 and 50 % CO2, 20 VPM PH3 alone and Mixtures of 20 VPM PH3 + 25 and 50 % CO2 at 26±1 °C.

Table (21): Lethal time values (LT_{50}, LT_{90} and LT_{99}), slope of regression line and categories of joint action for *R. dominica* (F.) exposed to phosphine alone and to mixtures of phosphine + CO_2 at 6±1°C.

Treatment	Stage	Lethal times (hr), their 95% confidence limits and categories of joint action						
		LT_{50}	C	LT_{90}	C	LT_{99}	C	Slope ± SE
20 vpm PH_3 alone	Adult	25 (22-29)	-	98 (77-125)	-	300 (205- 438)	-	2.15±0.44
	Larva	30 (25-37)	-	282 (194-409)	-	1771 (906-3461)	-	1.31±0.24
	Pupa	29 (24-35)	-	267 (183-391)	-	1661 (868-3177)	-	1.32±0.19
	Egg	59 (46-61)	-	278 (209-370)	-	1089 (677-1751)	-	1.76±0.48
20 vpm PH_3 + 25% v/v CO_2	Adult	3 (3- 4)	s	11 (8- 14)	s	29 (19- 46)	s	2.40±0.25
	Larva	17 (14-21)	s	94 (73-121)	s	382 (242-602)	s	1.71±0.17
	Pupa	16 (14-19)	s	95 (74-121)	i	399 (263-605)	i	1.67±0.16
	Egg	16 (13-19)	s	119 (89-158)	i	618 (373-1025)	s	1.46±0.26
20 vpm PH_3 + 50% v/v CO_2	Adult	4 (3- 4)	s	11 (8- 14)	s	26 (17- 39)	s	2.70±0.33
	Larva	6 (5- 8)	s	49 (37- 64)	s	258 (161-412)	s	1.45±2.30
	Pupa	12 (10-15)	s	83 (65-108)	i	397 (254-621)	a	1.54±0.61
	Egg	10 (9-12)	s	42 (35- 51)	s	134 (98-183)	s	2.08±0.78

a = antagonistic effect.
c = category of joint action.
i = independent joint action (additive effect)
s = synergistic effect.

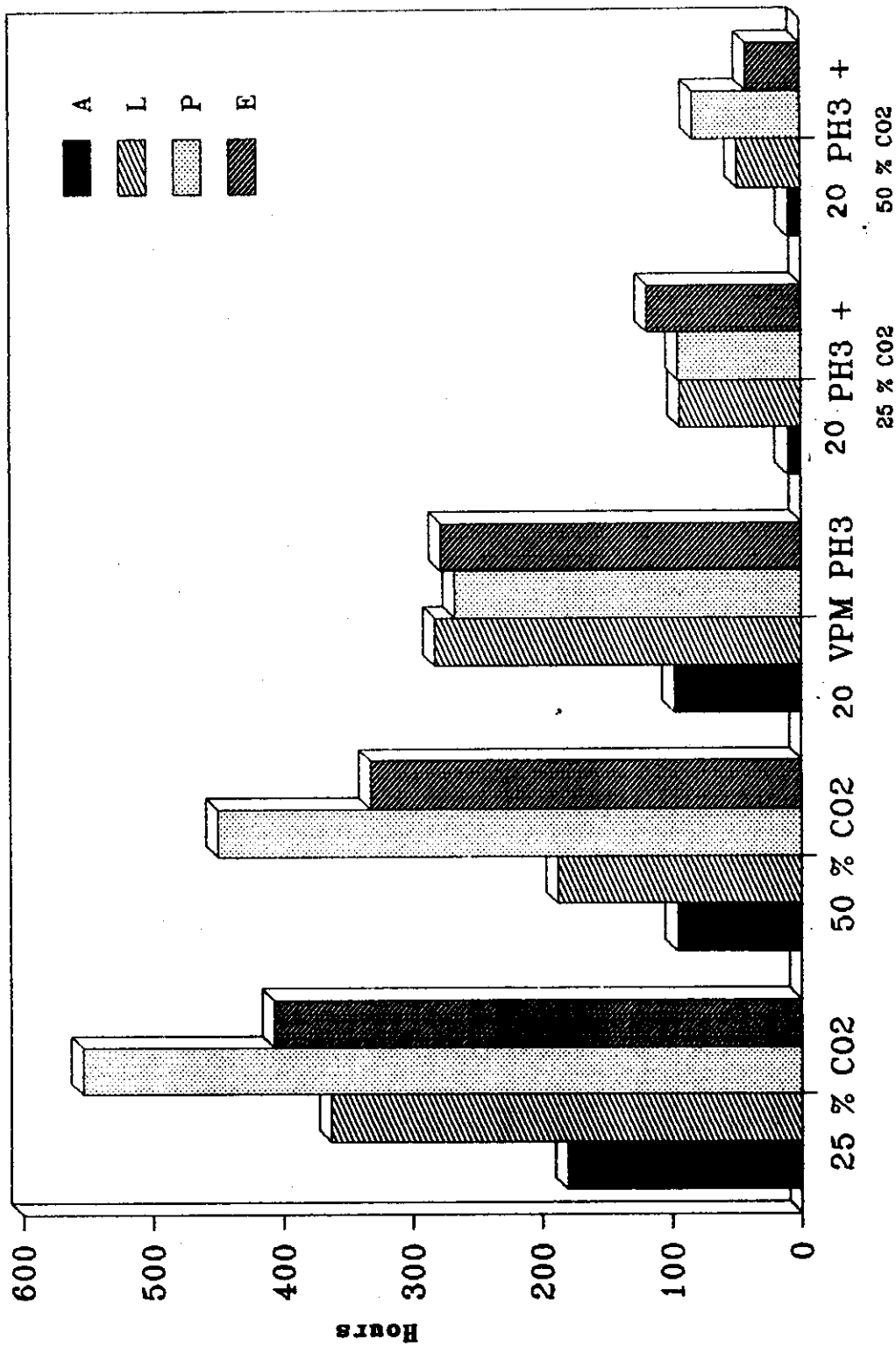

Fig. (9) : Time to 90 % mortality for the different stages of R. dominica (F) with 25 and 50 % CO_2, 20 VPM PH3 alone and Mixtures of 20 VPM PH3 + 25 and 50 % CO_2 at 26±1 °C.

Results indicate that the lethal time values achieved with the mixtures of PH_3 + CO_2 for the various stages of R. dominica were, however, less than those obtained with PH_3 alone, and the values achieved at lower temperature were greater than those obtained at higher one. For example the lethal exposure values required to achieve 90% mortility for the various stages at 26±1°C (see also Fig., 8) were (16, 44, 133 and 133 hr) with 20 vpm PH_3 alone, (4, 35, 70 and 62 hr) with 20 vpm PH_3 + 25% CO_2, and (7, 37, 69 and 37 hr) with the mixture of 20 vpm PH_3 + 50% CO_2 for the adult, larval, pupal and egg stage, respectively.

The corresponding values at 6±1°C (see Fig., 9) were (98, 282, 267 and 278 hr) with 20 vpm PH_3 alone, (11, 94, 95 and 119 hr) with 20 vpm PH_3 + 25% CO_2, and (11, 49, 83 and 42 hr) with the mixture of phosphine + 50% CO_2, for the forementioned various stages of R. dominica, respectively.

The lethal time values, slope of regression line, and categories of joint action for the various stages of R. dominica exposed to 40 vpm PH_3 and to mixtures of 40 vpm PH_3 + 25 and 50% CO_2 at 26±1°C and 6±1°C are given in Tables (22 and 23) and Figures (10 and 11).

Results revealed that the lethal time values recorded for mixtures of phosphine + carbon dioxide were obvious shorter than those obtained with phosphine alone and these

Table (22): Lethal time values (LT_{50}, LT_{90} and LT_{99}), slope of regression line and categories of joint action for R. dominica (F.) exposed to phosphine alone and to mixtures of phosphine + CO_2 at 26±1°C.

Treatment	Stage	Lethal times (hr), their 95% confidence limits and categories of joint action						
		LT_{50}	C	LT_{90}	C	LT_{99}	C	Slope ± SE
40 vpm PH_3 alone	Adult	7 (6- 8)	-	15 (13-18)	-	28 (21- 38)	-	3.81±0.30
	Larva	11 (10-12)	-	37 (31-44)	-	100 (75-132)	-	2.42±3.44
	Pupa	8 (7-10)	-	27 (22-32)	-	68 (49- 93)	-	2.56±1.13
	Egg	30 (26-36)	-	97 (77-123)	-	253 (169-379)	-	2.52±0.01
40 vpm PH_3 + 25% v/v CO_2	Adult	1 (1- 2)	s	3 (2- 4)	s	5 (3- 9)	s	4.30±0.18
	Larva	6 (5- 7)	s	28 (23-35)	s	98 (69-139)	s	1.93±0.70
	Pupa	8 (6- 9)	i	22 (17-27)	i	51 (36- 73)	i	2.81±0.78
	Egg	8 (7-10)	i	33 (27-40)	i	101 (74-138)	a	2.14±0.82
40 vpm PH_3 + 50% v/v CO_2	Adult	1 (1- 2)	s	7 (5- 9)	s	25 (12- 50)	s	3.19±0.89
	Larva	6 (5- 7)	s	14 (11-18)	s	29 (21- 42)	s	2.29±0.59
	Pupa	8 (7- 9)	i	32 (27-40)	i	102 (75-139)	a	2.14±1.33
	Egg	9 (8-11)	s	32 (26-39)	s	89 (64-124)	s	2.20±0.74

a = antagonistic effect.
c = category of joint action.
i = independent joint action (additive effect)
s = synergistic effect.

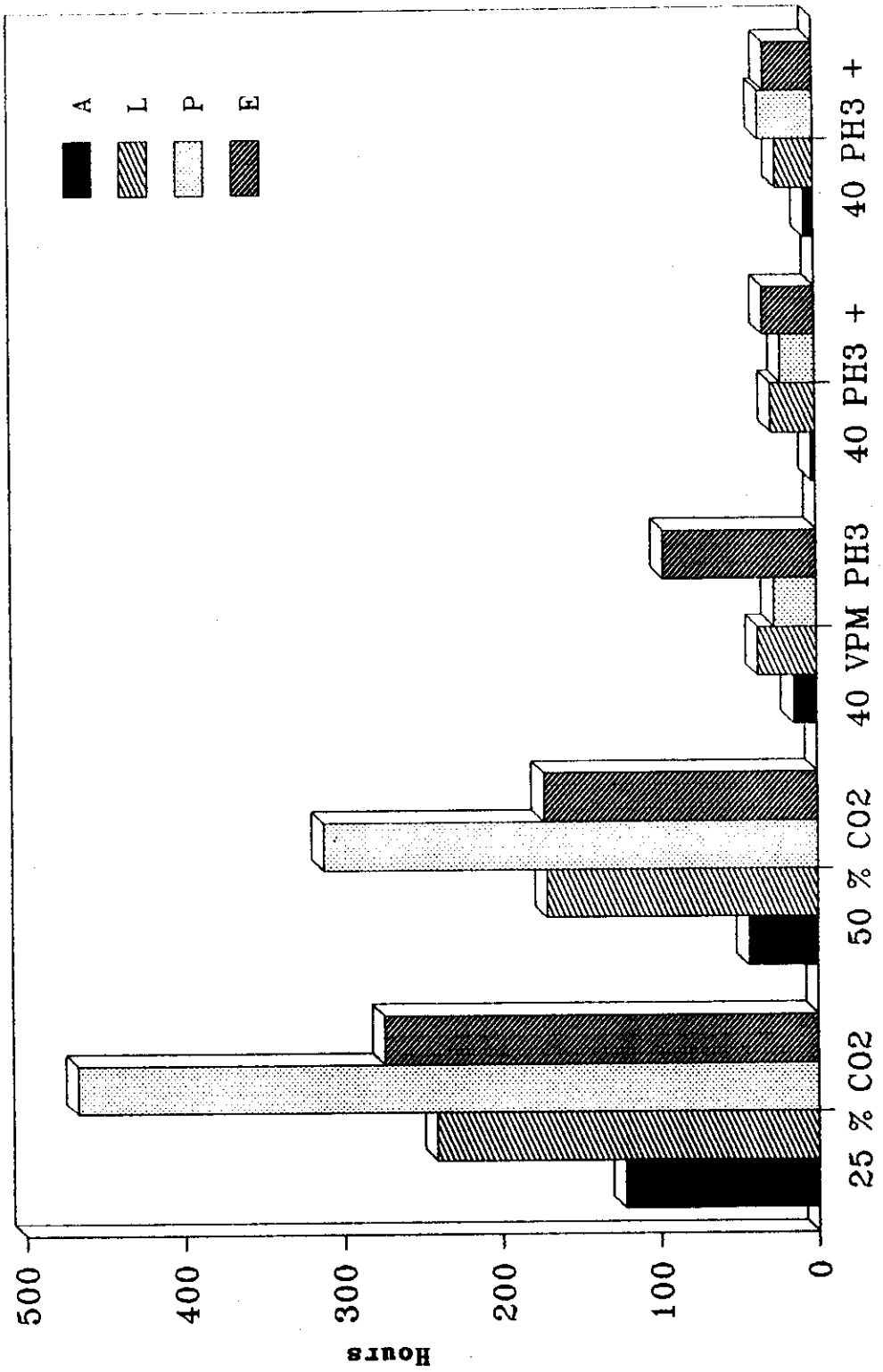

Fig. (10) : Time to 90 % mortality for the different stages of R. dominica (F) with 25 and 50 % CO2, 40 VPM PH3 alone and Mixtures of 40 VPM PH3 + 25 and 50 % CO2 at 26±1 °C.

Table (23): Lethal time values (LT_{50}, LT_{90} and LT_{99}), slope of regression line and categories of joint action for R. dominica (F.) exposed to phosphine alone and to mixtures of phosphine + CO_2 at 6±1°C.

Treatment	Stage	Lethal times (hr), their 95% confidence limits and categories of joint action						
		LT_{50}	C	LT_{90}	C	LT_{99}	C	Slope ± SE
40 vpm PH_3 alone	Adult	11 (10-13)	-	30 (25-35)	-	66 (51-85)	-	3.00±1.92
	Larva	23 (19-28)	-	176 (121-256)	-	927 (485-1769)	-	1.45±0.28
	Pupa	18 (15-23)	-	161 (109-239)	-	950 (482-1909)	-	1.35±0.11
	Egg	22 (18-27)	-	149 (107-209)	-	717 (404-1274)	-	1.53±0.10
40 vpm PH_3 + 25% v/v CO_2	Adult	5 (4- 5)	s	18 (14- 22)	s	54 (36- 79)	s	2.16±0.34
	Larva	12 (9-14)	s	48 (40- 59)	s	156 (111-219)	s	1.89±1.09
	Pupa	13 (11-16)	s	83 (65-106)	i	372 (242-570)	i	1.61±0.50
	Egg	10 (8-13)	s	46 (37- 56)	i	157 (110-225)	i	1.95±1.04
40 vpm PH_3 + 50% v/v CO_2	Adult	3 (3- 4)	s	13 (10- 16)	s	39 (27- 56)	s	2.14±0.94
	Larva	6 (5- 7)	s	34 (27- 42)	s	134 (92-195)	s	1.74±1.09
	Pupa	12 (10-14)	s	50 (41- 61)	i	162 (121-218)	i	2.05±0.96
	Egg	13 (11-16)	s	75 (59- 95)	s	320 (213-479)	s	1.67±0.35

a = antagonistic effect.
c = category of joint action.
i = independent joint action (additive effect)
s = synergistic effect.

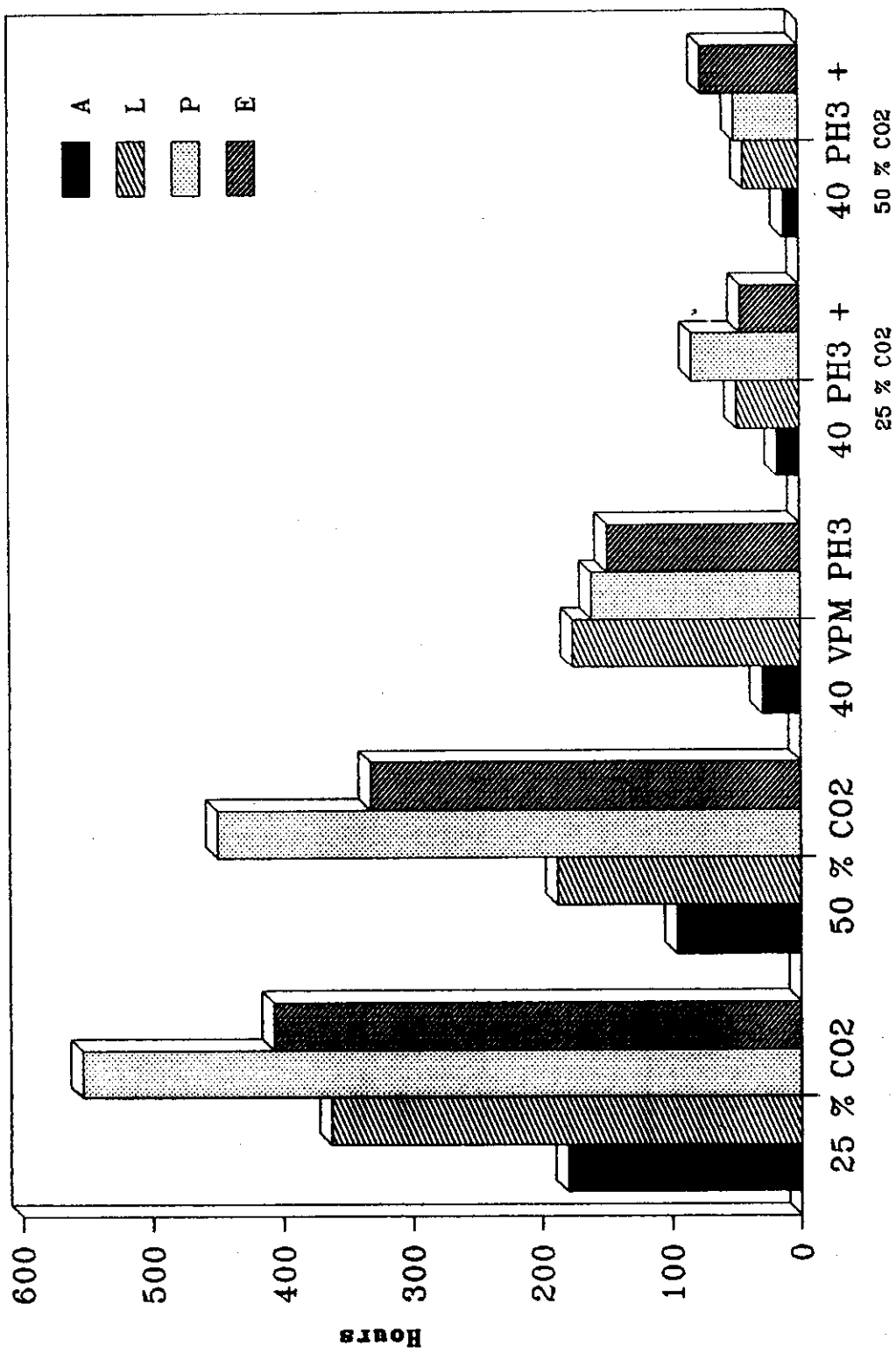

Fig. (11) : Time to 90 % mortality for the different stages of R. dominica (F) with 25 and 50 % CO2, 40 VPM PH3 alone and Mixtures of 40 VPM PH3 + 25 and 50 % CO2 at 5±1 °C.

values were longer at lower temperature than at higher one. For example the lethal time values required to achieve 90% kill for the various stages of R. dominica at 26±1°C were (15, 37, 27 and 97 hr) with 40 vpm PH_3 alone, (3, 28, 22 and 33 hr) with the mixture of 40 vpm PH_3 + 25% CO_2, and (7, 14, 32 and 32 hr) with the mixture contained 40 vpm PH_3 + 50% CO_2, for the adult, larval, pupal, and egg stage, respectively.

The corresponding values at 6±1°C were (30, 176, 161 and 149 hr) with phosphine alone, (18, 48, 83 and 46 hr) with the mixture of phosphine + 25% CO_2, and (13, 34, 50 and 75 hr) with the mixture of phosphine + 50% CO_2 for the forementioned various stages, respectively.

Results obtained at 26±1°C and 6±1°C revealed that a synergistic action was proved at the LT_{90} level with the mixtures of phosphine + carbon dioxide for the adults. A synergistic effect was observed at 26±1°C for the larval stage by mixtures contained 40 vpm PH_3 + 25 and 50% CO_2. An additive effect was found by mixtures of 20 vpm PH_3 + 25 and 50% CO_2.

At 6±1°C, all mixtures of PH_3 + CO_2 had shown a synergistic effect for the larvae. For the pupal stage, an independent joint action was proved at the two test temperatures by the mixtures of PH_3 + CO_2 with exception of mixture contained 20 vpm PH_3 + 50% CO_2 at 26±1°C, which showed an antagonistic effect.

For the eggs, a synergistic action, as well as an independent joint action were observed by the mixtures of phosphine + carbon dioxide at the two test temperatures.

3.3. Efficacy of phosphine alone and in mixtures with carbon dioxide against the various stages of C. maculatus:

Tables (24 and 25) demonstrate the lethal time values, slope of regression line and categories of joint action for the various stages of C. maculatus exposed to phosphine alone (20 vpm in air) and to mixtures of phosphine + 25 and 50% CO_2 at 26±1°C and 6±1°C.

Data indicate that the lethal time values required to achieve 90% mortality at 26±1°C (see Fig., 12) for the various stages of C. maculatus were (22, 67, 60 and 120 hr) with 20 vpm PH_3 alone, (14, 66, 43 and 68 hr) with the mixture of 20 vpm PH_3 + 25% CO_2, and (5, 28, 58 and 44 hr) with the mixture of phosphine + 50% CO_2, for the adult, larval, pupal and egg stage, respectively.

The corresponding values at 6±1°C (see Fig., 13) were (122, 211, 158 and 254 hr) with phosphine alone, (17, 64, 113 and 119 hr) with the mixture of phosphine + 25% CO_2 and (12, 82, 122 and 103 hr) with the mixture contained 20 vpm PH_3 + 50% CO_2, for the forementioned various stages, respectively.

Table (24): Lethal time values (LT_{50}, LT_{90} and LT_{99}), slope of regression line and categories of joint action for C. maculatus (F.) exposed to phosphine alone and to mixtures of phosphine + CO_2 at 26±1°C.

Treatment	Stage	Lethal times (hr), their 95% confidence limits and categories of joint action						
		LT_{50}	C	LT_{90}	C	LT_{99}	C	Slope ± SE
20 vpm PH_3 alone	Adult	7 (6- 8)	-	22 (16-29)	-	56 (34- 93)	-	2.49±0.17
	Larva	38 (34-42)	-	67 (57-79)	-	107 (82-140)	-	5.14±0.02
	Pupa	34 (31-38)	-	60 (51-69)	-	94 (73-121)	-	5.27±0.07
	Egg	54 (48-61)	-	120 (101-141)	-	209 (174-303)	-	3.69±0.02
20 vpm PH_3 + 25% v/v CO_2	Adult	5 (4- 6)	s	14 (11-17)	s	32 (22- 47)	s	2.80±0.22
	Larva	15 (12-17)	s	66 (51-86)	s	225 (145-347)	i	2.71±0.43
	Pupa	12 (10-14)	s	43 (36-52)	i	124 (92-167)	a	2.28±0.94
	Egg	14 (11-17)	s	68 (54-86)	i	251 (166-278)	a	1.96±3.69
20 vpm PH_3 + 50% v/v CO_2	Adult	2 (1- 2)	s	5 (4- 7)	s	13 (9- 19)	s	2.73±0.24
	Larva	7 (6- 9)	s	28 (22-34)	s	81 (58-115)	i	2.22±0.79
	Pupa	9 (8-11)	i	58 (46-74)	i	258 (174-382)	a	1.61±0.23
	Egg	11 (9-12)	s	44 (37-53)	i	144 (104-197)	a	2.05±0.89

a = antagonistic effect.
c = category of joint action.
i = independent joint action (additive effect)
s = synergistic effect.

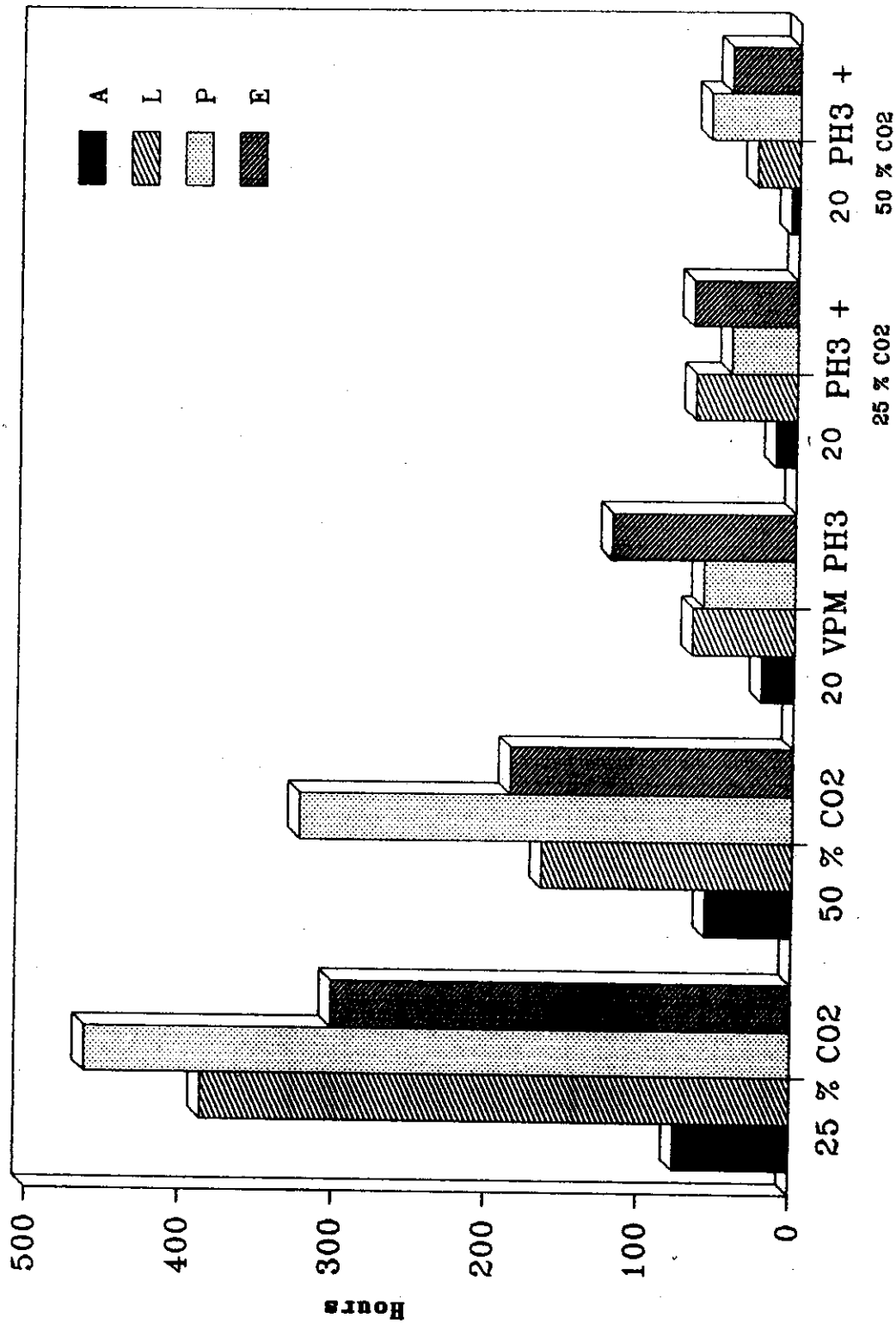

Fig. (12) : Time to 90 % mortality for the different stages of C. maculatus (F) with 25 and 50 % CO_2, 20 VPM PH_3 alone and Mixtures of 20 VPM PH_3 + 25 and 50 % CO_2 at 26±1 °C.

Table (25): Lethal time values (LT_{50}, LT_{90} and LT_{99}), slope of regression line and categories of joint action for C. maculatus (F.) exposed to phosphine alone and to mixtures of phosphine + CO_2 at 6±1°C.

Treatment	Stage	Lethal times (hr), their 95% confidence limits and categories of joint action						
		LT_{50}	C	LT_{90}	C	LT_{99}	C	Slope ±.SE
20 vpm PH_3 alone	Adult	23 (19-27)	-	122 (89-169)	-	487 (294-806)	-	1.74±0.81
	Larva	30 (25-36)	-	211 (145-307)	-	1036 (556-1934)	-	1.51±0.15
	Pupa	18 (15-22)	-	158 (107-234)	-	938 (467-1886)	-	1.35±0.31
	Egg	50 (42-59)	-	254 (247-505)	-	1761 (963-3219)	-	1.50±0.53
20 vpm PH_3 + 25% v/v CO_2	Adult	6 (5- 7)	s	17 (13- 21)	s	39 (28- 56)	s	2.75±0.85
	Larva	17 (15-20)	s	64 (52- 78)	s	183 (130-259)	s	1.28±2.78
	Pupa	16 (13-19)	s	113 (86-150)	i	562 (344-918)	i	1.50±0.32
	Egg	22 (18-26)	s	119 (92-154)	i	476 (301-752)	i	1.73±0.11
20 vpm PH_3 + 50% v/v CO_2	Adult	3 (3- 4)	s	12 (10- 16)	s	36 (23- 57)	s	2.21±0.75
	Larva	8 (6-10)	s	82 (59-114)	s	559 (308-1015)	s	1.25±3.82
	Pupa	17 (14-21)	i	122 (92-161)	i	605 (370-989)	i	1.50±0.29
	Egg	16 (12-20)	s	103 (78-137)	a	486 (287-823)	a	1.55±0.20

a = antagonistic effect.
c = category of joint action.
i = independent joint action (additive effect)
s = synergistic effect.

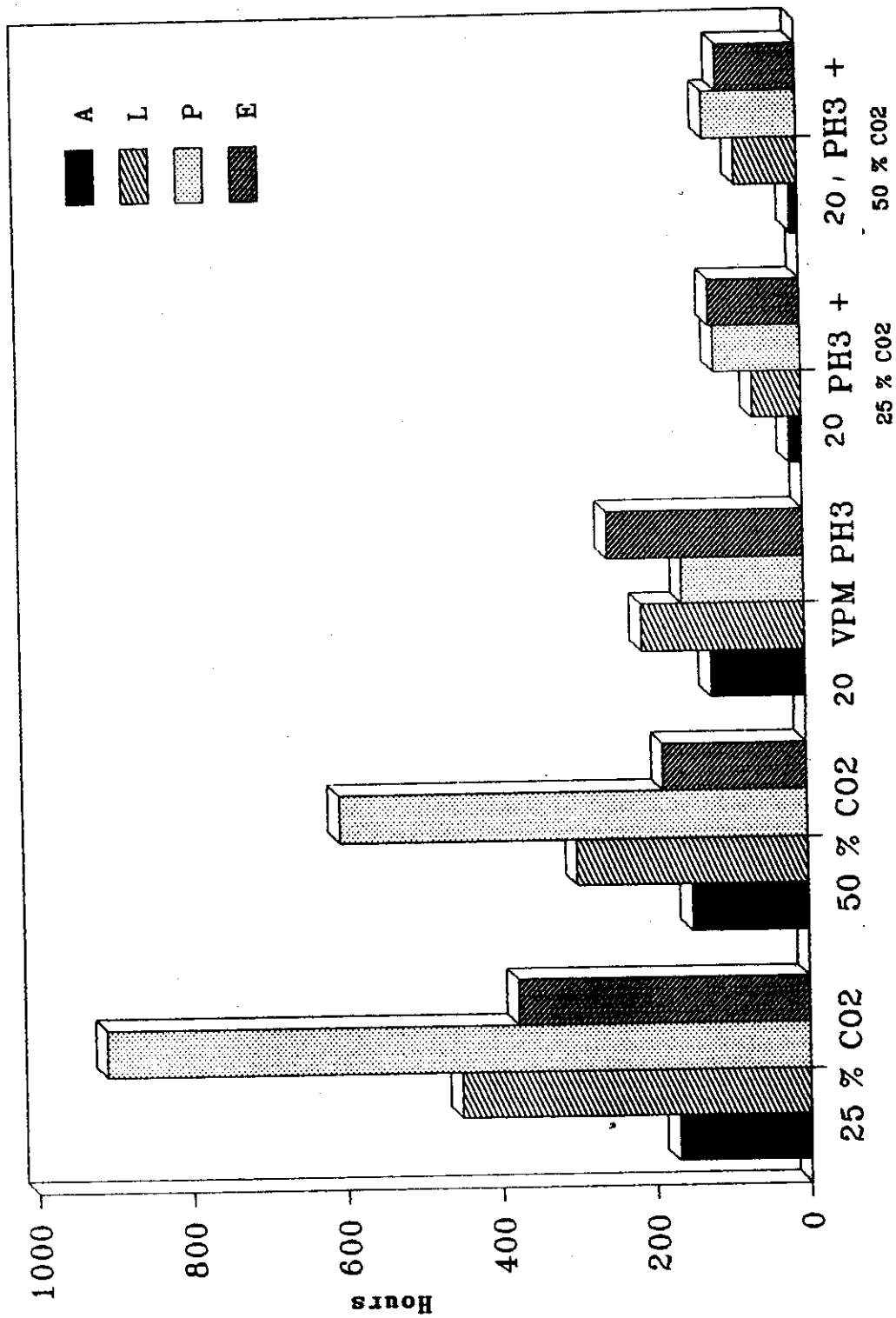

Fig. (13) : Time to 90 % mortality for the different stages of C. maculatus (F) with 25 and 50 % CO_2, 20 VPM PH_3 alone and Mixtures of 20 VPM PH_3 + 25 and 50 % CO_2 at 26±1 °C.

Tables (26 and 27) show the lethal time values, slope of regression line and categories of joint action for the various stages of C. maculatus exposed to phosphine alone (40 vpm) and to mixtures of 40 vpm PH_3 + 25 and 50% CO_2 at 26±1°C and 6±1°C.

Results indicate that the lethal exposure values required to obtain 90% mortality for the various stages of C. maculatus at 26±1°C (see Fig., 14) were (17, 59, 32 and 98 hr) with phosphine alone, (4, 15, 32 and 32 hr) with the mixture of phosphine + 25% CO_2 and (7, 14, 32 and 32 hr) with the mixture of PH_3 + 50% CO_2, for the adult, larval, pupal and egg stage, respectively.

The corresponding values at 6±1°C (see Fig., 15) were (74, 119, 80 and 135 hr) with phosphine alone, (14, 105, 79 and 80 hr) with phosphine + 25% CO_2 and (4, 35, 40 and 78 hr) with phosphine + 50% CO_2, for the forementioned various stages of this pest, respectively.

Results recorded at 26±1°C and 6±1°C showed that a synergistic effect was observed at the LT_{90} level with the mixtures of phosphine + carbon dioxide for the adult and larval stages.

For the pupal stage, an independent joint action was proved by the mixtures of PH_3 + CO_2 at the two test temperatures.

Table (26): Lethal time values (LT_{50}, LT_{90} and LT_{99}), slope of regression line and categories of joint action for C. maculatus (F.) exposed to phosphine alone and to mixtures of phosphine + CO_2 at 26±1°C.

Treatment	Stage	Lethal times (hr), their 95% confidence limits and categories of joint action						
		LT_{50}	C	LT_{90}	C	LT_{99}	C	Slope ± SE
40 vpm PH_3 alone	Adult	9 (8-10)	-	17 (15-20)	-	29 (23- 37)	-	4.67±0.50
	Larva	27 (24-30)	-	59 (50-69)	-	112 (86-147)	-	3.75±0.02
	Pupa	10 (9-12)	-	32 (26-39)	-	80 (57-110)	-	2.61±0.57
	Egg	40 (38-42)	-	98 (91-105)	-	204 (180-233)	-	3.26±0.03
40 vpm PH_3 + 25% v/v CO_2	Adult	2 (1- 2)	s	4 (3- 6)	s	9 (6- 13)	s	3.27±0.44
	Larva	5 (5- 6)	s	15 (11-18)	s	32 (22- 47)	s	3.00±1.17
	Pupa	8 (7-10)	s	32 (26-41)	i	101 (68-148)	a	2.12±0.66
	Egg	9 (8-10)	s	52 (39-69)	s	93 (69-126)	s	2.28±0.58
40 vpm PH_3 + 50% v/v CO_2	Adult	1 (1- 2)	s	7 (5- 9)	s	25 (12- 50)	s	1.85±2.49
	Larva	6 (5- 7)	s	14 (11-18)	s	29 (21- 42)	s	3.28±0.25
	Pupa	8 (7- 9)	i	32 (27-40)	i	102 (75-139)	i	2.11±0.53
	Egg	9 (8-10)	s	32 (26-39)	s	89 (64-124)	s	2.32±0.56

a = antagonistic effect.
c = category of joint action.
i = independent joint action (additive effect)
s = synergistic effect.

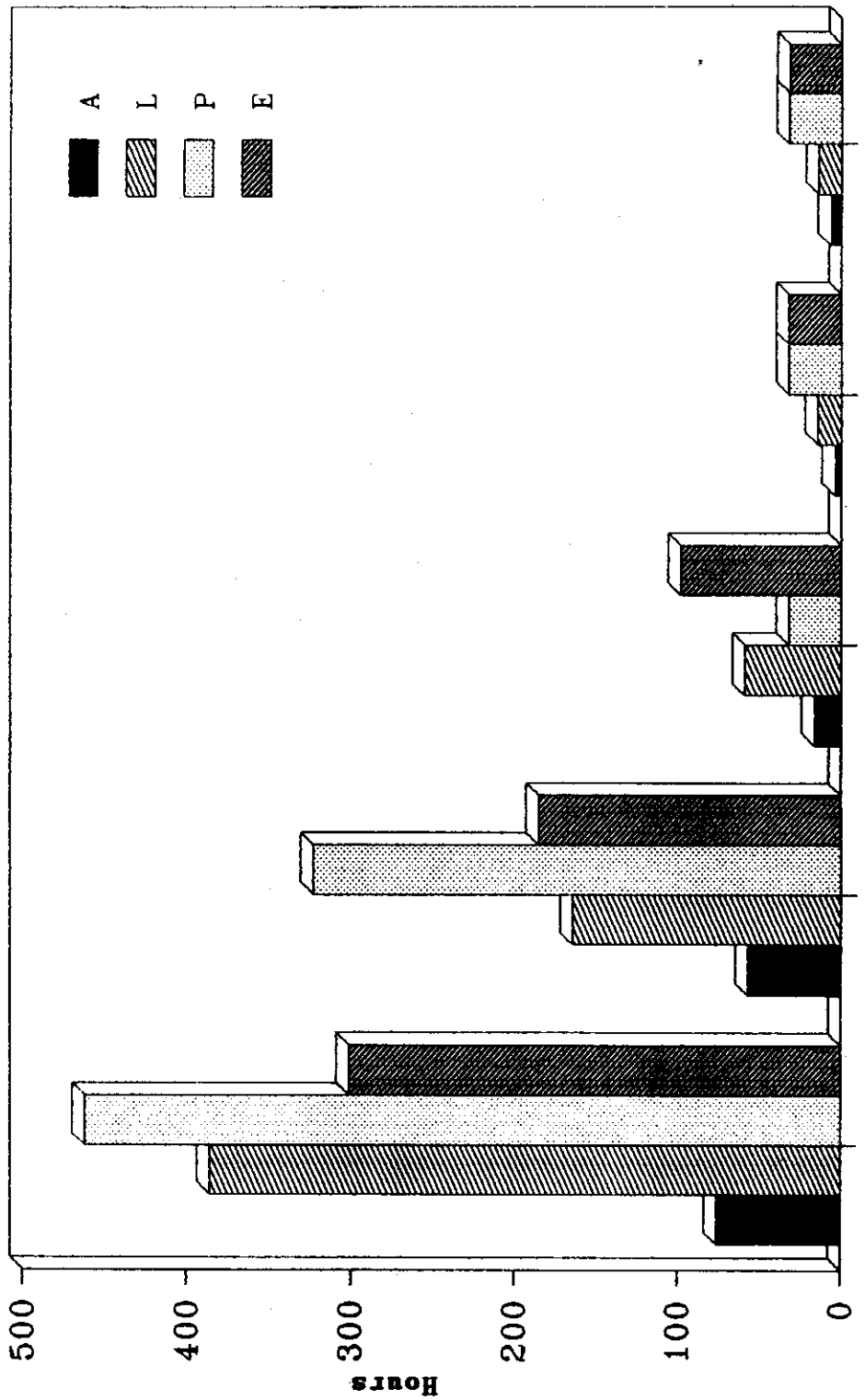

Fig. (14) : Time to 90 % mortality for the different stages of C. maculatus (F) with 25 and 50 % CO_2, 40 VPM PH_3 alone and Mixtures of 40 VPM PH_3 + 25 and 50 % CO_2 at 26±1 °C.

Table (27): Lethal time values (LT_{50}, LT_{90} and LT_{99}), slope of regression line and categories of joint action for C. maculatus (F.) exposed to phosphine alone and to mixtures of phosphine + CO_2 at 6±1°C.

Treatment	Stage	Lethal times (hr), their 95% confidence limits and categories of joint action						
		LT_{50}	C	LT_{90}	C	LT_{99}	C	Slope,±,SE
40 vpm PH_3 alone	Adult	12 (10-14)	-	74 (55-101)	-	335 (201-557)	-	1.60±0.32
	Larva	35 (30-39)	-	119 (97-146)	-	329 (237-455)	-	2.37±1.62
	Pupa	10 (8-13)	-	80 (58-111)	-	433 (237-792)	-	1.43±1.23
	Egg	31 (27-36)	-	135 (104-175)	-	453 (296-693)	-	1.98±0.49
40 vpm PH_3 + 25% v/v CO_2	Adult	3 (3- 4)	s	14 (11- 18)	s	46 (29- 72)	s	2.07±0.42
	Larva	17 (14-20)	s	105 (81-137)	s	476 (302-752)	i	1.59±0.84
	Pupa	13 (11-16)	i	79 (62-100)	i	338 (223-514)	a	1.65±0.34
	Egg	15 (12-18)	s	80 (62-102)	i	317 (204-491)	a	1.74±0.14
40 vpm PH_3 + 50% v/v CO_2	Adult	2 (1- 2)	s	4 (4- 5)	s	10 (7- 13)	s	3.09±0.65
	Larva	6 (5- 7)	s	35 (28- 44)	s	147 (99-218)	s	1.68±1.32
	Pupa	12 (10-14)	i	40 (33- 49)	i	110 (82-149)	i	2.38±0.93
	Egg	15 (12-17)	s	78 (62- 98)	i	306 (207-450)	i	1.76±4.05

a = antagonistic effect. i = independent joint action (additive effect)

c = category of joint action. s = synergistic effect.

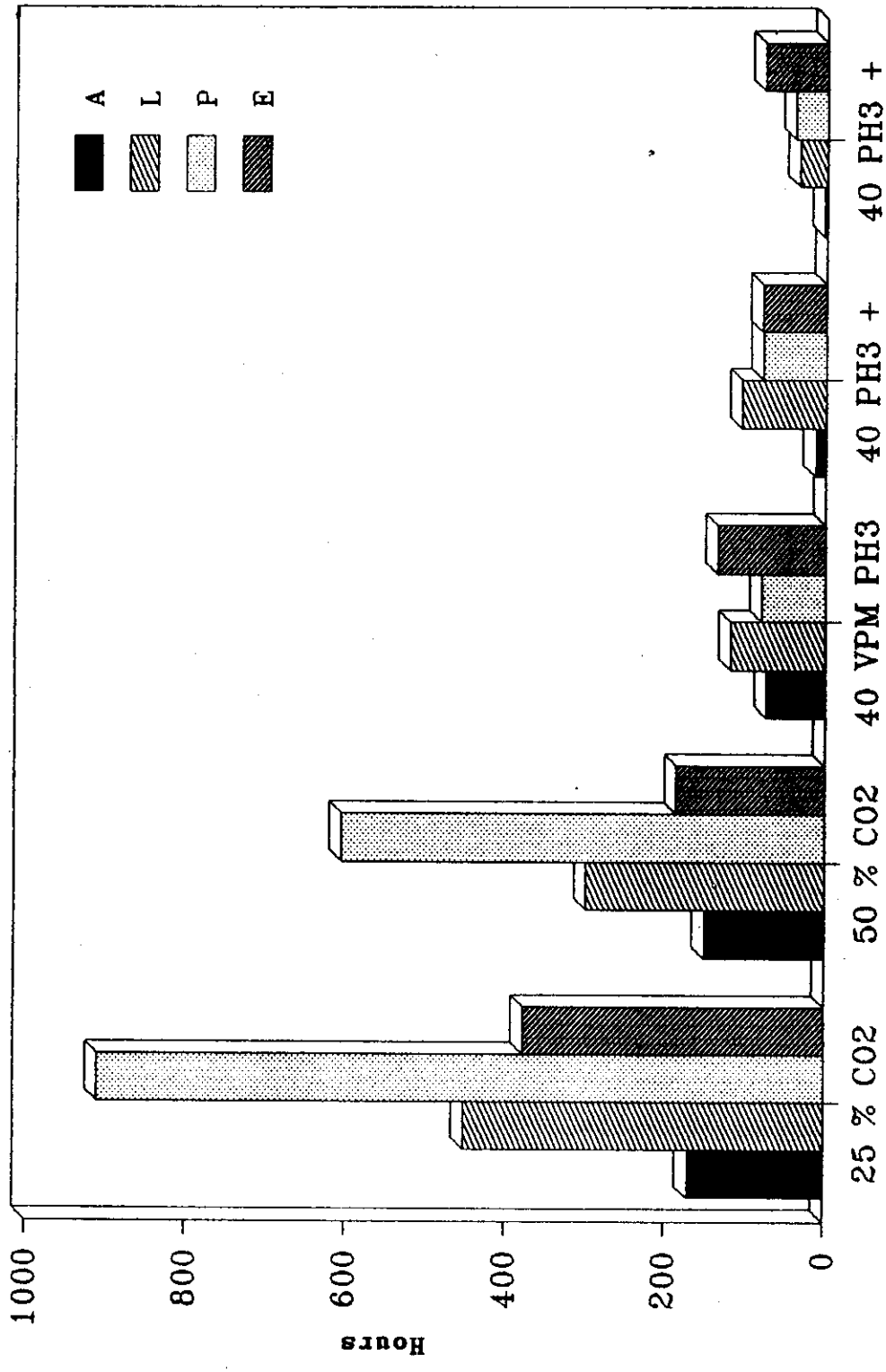

Fig. (15) : Time to 90 % mortality for the different stages of C. maculatus (F) with 25 and 50 % CO_2, 40 VPM PH_3 alone and Mixtures of 40 VPM PH_3 + 25 and 50 % CO_2 at 26±1 °C.

4- Categories of joint action obtained by mixtures of phosphine + carbon dioxide for the various stages of the tested insects:

4.1. Categories of joint action at the LT_{50} level:

For the adults of all tested insect species, the calculated or corrected values for mortality due to phosphine in the mixtures of PH_3 + CO_2, were significantly less at the LT_{50} level, than those observed in phosphine alone. That is to say, carbon dioxide synergized the toxicity of phosphine against the adults of S. oryzae, R. dominica and C. maculatus by using various mixtures of PH_3 + CO_2 at the two test temperatures. Synergism at the LT_{50} level was also demonstrated for larvae and eggs of the three insect species with various mixtures of PH_3 + CO_2 tested at 26±1°C and 6±1°C.

The action of carbon dioxide and phosphine was additive at the LT_{50} level for the pupae of S. oryzae and C. maculatus by the various mixtures of PH_3 + CO_2 tested at the two test temperatures. In case of R. dominica - pupae, a synergistic action was proved at the LT_{50} level with exception of the mixture contained 40 vpm PH_3 + 50% CO_2 at 26±1°C, whereby an additive effect was observed.

4.2. Categories of joint action at the LT_{99} level:

The type of joint action between phosphine and carbon dioxide was more manifold at the LT_{99} level than at the LT_{50} level.

For adults of the three tested species, the action of carbon dioxide and phosphine was synergistic at the LT_{99} level by all mixtures tested at the two test temperatures with exception of mixture contained 20 vpm PH_3 + 25% CO_2 at 26±1°C in case of S. oryzae adults, whereby an additive effect was found.

For Larvae of S. oryzae, synergism at the LT_{99} level was observed with all mixtures of PH_3 + CO_2 investigated at the two test temperatures.

For larvae of R. dominica, synergism at the LT_{99} level was also demonstrated by mixtures of PH_3 + CO_2 at the two test temperatures, with exception of mixtures contained 20 vpm PH_3 + 25 and 50% CO_2 at 26±1°C, whereby an additive effect was proved.

For Larvae of C. maculatus at 26±1°C, a synergistic effect was found by mixtures contained 40 vpm PH_3 + 25 and 50% CO_2, on the other hand mixtures contained 20 vpm PH_3 + 25 and 50% CO_2 had shown an additive effect. At 6±1°C, a synergistic effect at the LT_{99} level was proved for C. maculatus - larvae by mixtures of phosphine + carbon dioxide with exception of mixture contained 40 vpm PH_3 + 25% CO_2.

The results obtained revealed that the type of joint action between phosphine and carbon dioxide at the LT_{99}

level was more complex for pupae and eggs than for addults and larvae.

For pupae of S. oryzae at 26±1°C, an independent joint action was obtained by mixtures contained 20 vpm PH_3 + 25 and 50% CO_2, and an antagonistic effect was observed by mixtures contained 40 vpm PH_3 + 25 and 50% CO_2. At 6±1°C, an independent joint action was found with exception of mixture contained 20 vpm PH_3 + 50% CO_2, whereby an antagonistic effect was observed.

For pupae of R. dominica at 26±1°C, the action between phosphine and carbon dioxide at the LT_{99} level was antagonistic except for 40 vpm PH_3 + 25% CO_2, whereby an additive effect was found. Contrary, at lower temperature, the action between phosphine and carbon dioxide was additive with exception of mixture contained 20 vpm PH_3 + 50% CO_2, which induced an antagonistic action.

For pupae of C. maculatus at 26±1°C, an antagonistic effect was observed except for mixture contained 40 vpm PH_3 + 50 CO_2, which induced an additive effect. At 6±1°C, an independent joint action was proved for the pupae at the LT_{99} level except for mixture contained 40 vpm PH_3 + 25% CO_2.

For eggs of S. oryzae at 26±1°C, the action between phosphine and carbon dioxide was antagonistic by addition

of 25 and 50% CO_2 to 20 vpm PH_3. Contrary, the addition of carbon dioxide to 40 vpm PH_3, induced a synergistic action.

At 6±1°C, the same result was recorded by mixtures contained 20 vpm PH_3 + 25 and 50% CO_2, but the other mixtures of PH_3 + CO_2 resulted an additive effect.

For eggs of R. dominica, the addition of 50% CO_2 to 20 and 40 vpm PH_3 in mixtures at higher and lower temperatures induced a synergistic effect, but the addition of 25% CO_2 to phosphine resulted in an additive effect except for mixture contained 40 vpm PH_3 + 25% CO_2 at 26±1°C, whereby an antagonistic effect was found.

For eggs of C. maculatus at 26±1°C, a synergistic action was observed by mixtures contained 40 vpm PH_3 + 25% and 50% CO_2. Contrary, an antagonistic action was found by mixtures contained 20 vpm PH_3 + 25 and 50% CO_2.

At 6±1°C, the results were contradictory at the LT_{99} level for the eggs of C. maculatus (Tables, 24-27).

An additive effect was observed by mixtures of 20 vpm PH_3 + 25% CO_2 and 40 vpm PH_3 + 50% CO_2. Contrary, an antagonistic effect was found by mixture of 20 vpm PH_3 + 50% CO_2 as well as 40 vpm PH_3 + 25% CO_2.

Results obtained are in harmony with the findings of some investigators (Desmarchelier, 1984 and El-Lakwah et al 1989 and 1991).

El-Lakwah et al. (1989) studied the effect of the inert gas carbon dioxide on the efficacy of phosphine against the adults of T. castaneum and S. oryzae at 28°C. Results showed that, mixtures of varying concentrations of CO_2 + LC_{50} of PH_3 induced higher adult mortalities.

The same authors (1991) investigated the efficiency of phosphine alone and in mixtures with carbon dioxide aganist S. cerealella (Olivier). They found that larval mortalities obtained from mixtures of the LC_{50} of PH_3 + CO_2 were significantly higher than those of each gas alone, whereby a synergistic action was proved for all exposure periods at 20 and 28°C. An increase in pupal mortalities was achieved at all exposure periods with exception of 8 hr at 20°C, and an independent joint action was found at short and long exposures at 28°C.

Investigations conducted in the laboratory for comparing the efficacy of phosphine with that of mixtures of the gas plus carbon dioxide against diapause larvae of Trogoderma granarium showed that addition of varying concentrations of CO_2 (20, 50, 75 and 100%) to fixed PH_3-concentrations had a negative influence on phosphine efficacy against diapause larvae of khapra Beetle at 30°C

for short exposure periods of 18 and 24 hours. On the other hand, it was found that for longer exposure periods of 48 and 72 hr, the addition of CO_2 to phosphine induced significantly higher larval mortality than that by PH_3 alone, whereby an additive effect was proved for mixtures contained PH_3 + 75% and 100% CO_2. The addition of 20 and 50% CO_2 to PH_3 at 20°C did not show any increase in larval mortalities of the mixtures for exposure periods between 24-96 hours (El-Lakwah et al., 1989).

Kashi and Bond (1975) reported that CO_2 was found to potentiate the action of phosphine against a normal strain of T. confusum and against normal and resistant strains of S. granarius so that the length of the exposure period could be reduced.

Results obtained in this work on bioeffectiveness of mixing carbon dioxide to phosphine revealed that the two concentrations of CO_2 (25 and 50%) mixed with phosphine increased the efficiency of phosphine at the LT_{50} level against all stages of the insect species tested.

At the LT_{99} level, the addition of CO_2 to phosphine increased also the efficiency of phosphine against adults and larvae of the three insect species. For pupae and eggs, the addition of CO_2 to phosphine caused in some cases a rise in the efficacy of phosphine, but in other cases a decrease in the efficacy was observed.