Experimental Studies on the Resistance of the Rice Weevil, *Calandra oryzae* L., to Heat.*

II. Lethal Effects of Heat upon the Larvae and Pupae.

By

T. Tsuchiya and K. Kosaka.

[March 22, 1943]

Contents.

I. Introduction.

In the previous paper, the studies had been confined to the resistance of the adult rice weevils, *C. oryzae* L., to heat. The authors have conducted some experiments on the resistance of larvae and pupae-the problem which have been left almost untouched to this day. The results obtained are set forth below.

It is generally believed with regard to the rice weevil that of all the stages of development, the pupae are the most resistant to fumigants, owing partly to the wall of rice kernel which protects them from the direct contact. Is this also the case with respect to their resistance to heat? Is there any difference in true resistance

* Investigation aided by the Research Fund for Science from the Department of Education.

among adult, pupa and larva? In order to answer these questions, the following experiments have been carried out.

Materials and methods are all similar to those given in the previous paper except for the case particularly noted.

II. Paralytic and Lethal High Temperatures.

In physiology and ecology, the environmental temperatures are divided into several ranges, such as the zones of lethal high temperature, optimum temperature and lethal low temperature etc., according to their effects upon the life process of insects. However, strictly speaking, it is impossible to determine the lowest temperature which causes heat paralysis or thermal death in insects as the result of coagulation of protoplasm, because in the lethal actions of heat the temperature should be taken as a volume factor and not as an intensity one. Therefore, in this experiment, the authors were intended to determine the lowest temperature, a comparatively short exposure which results in paralysis or death in rice weevils, and call it for convenience sake "Paralytic high temperature" or "Lethal high temperature" respectively.

Naked larvae and pupae that had been taken out of the rice kernels were used as materials. The larvae which appeared to be in fourth instar from their size, and the pupae which displayed milky white colour, were exclusively employed.

These materials were exposed to the temperature which rose at a rate of 0.7°C. per minute beginning at 30°C. and when the aimed temperature was reached, they were held for 10 minutes. Insects thus treated were divided into two groups, namely, active and motionless. The latter was kept under optimum conditions for a week, during which time the state of daily recovery from heat paralysis was observed. The individuals that failed to recover within a week, were proved dead without exception from their apparent transformation and discolouration.

The results obtained are summarized in Table 1 and 2. They are the averages of eight tests, using 50 individuals in each test.

1. Paralytic High Temperature.

The individuals that were motionless directly after heat treatment include not only the temporarily but also the permanently paralyzed and the lethal ones. Up to as high temperature as 47°C., however, the number of motionless individuals may be taken to represent the number of paralyzed ones, since the mortality does not exceed 5%.

The motionless individuals, as is apparent in Table 1 and 2, appear first at 43°C. in larvae and at 42°C. in pupae. They reach 50% between 45° and 46°C. and 100% at 47°C. The relation between the percentage of motionless individuals and the temperature is shown in Fig. I, being represented by an S-shaped curve which

Table 1.

Temperatures which Cause either Heat Paralysis or Thermal Death in Larvae of Rice Weevil.

Temperature (°C.)	No. tested	Motionless individual		Dead individual		Temporarily paralyzed individual	
		No.	%	No.	%	No.	%
42	400	0	0	0	0	0	0
43	400	22	5.50	2	0.50	20	5.00
44	400	103	25.75	2	0.50	101	25.25
45	400	190	47.50	5	1.25	130	46.25
46	400	356	89.00	9	2.25	347	86.75
47	400	400	100.00	17	4.25	383	95.75
48	400	400	100.00	33	8.25	367	91.75
49	400	400	100.00	111	27.75	299	72.25
50	400	400	100.00	330	82.50	70	17.50
51	400	400	100.00	397	99.25	3	0.75
52	400	400	100.00	400	100.00	0	0

Individuals that were motionless immediately after treatment.

Table 2.

Temperatures which Cause either Heat Paralysis or Thermal Death in Pupae of Rice Weevil.

Temperature (°C.)	No. tested	Motionless individual		Dead individual		Temporarily paralyzed individual	
		No.	%	No.	%	No.	%
42	400	5	1.25	0	0	5	1.25
43	400	31	7.75	0	0	31	7.75
44	400	69	17.25	2	0.50	67	16.75
45	400	144	36.00	7	1.75	116	34.25
46	400	331	82.75	10	2.50	321	80.25
47	400	400	100.00	12	3.00	388	97.00
48	400	400	100.00	15	3.75	385	96.25
49	400	400	100.00	75	18.75	325	81.25
50	400	400	100.00	265	66.25	135	33.75
51	400	400	100.00	352	88.00	48	12.00
52	400	400	100.00	399	99.75	1	0.25

has often been encountered in the course of these works. It can be seen in Fig. I that the pupae show somewhat superior resistance to larvae though not so significant. According to the results in Report I, adult weevils seem to fall in paralysis at higher temperature than larvae and pupae.

Fig. I.

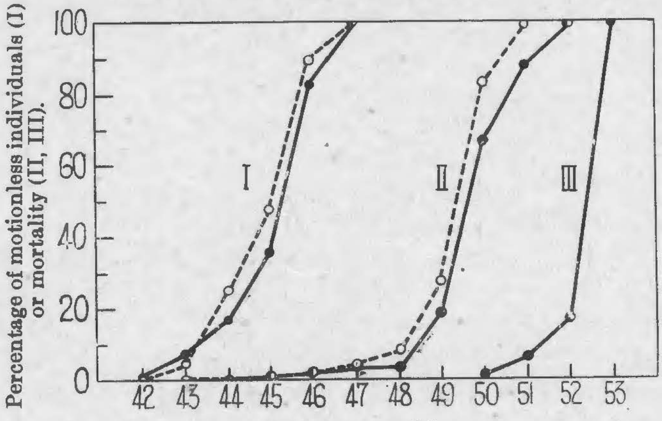
Temperatures which Cause Heat Paralysis or Thermal Death in Rice Weevil.

I. Relation between % of motionless individuals and temperature.

II. Relation between mortality and temperature.

Black line: pupa, dotted line: larva.

III. Relation between mortality and temperature in adult weevil.



2. Lethal High Temperature.

The relation between mortality and temperature is also represented by an S-shaped curve as is shown in Fig. I, from which it can be seen that the lethal individuals firstly appear at about 43°C. and reach 50% at 49° - 50°C. and 100% at 52°C. In comparison with these results the mortality of adult weevils that were subjected to the same treatment is given in Table 3 and Fig. I. These clearly show that the temperature which results in 100% mortality in adult weevils is 53°C., being higher by 1° than that of larvae or pupae.

Table 3.

Temperatures which Cause Thermal Death in Adult Rice Weevil.

Temperature (°C.)	No. tested	Mortionless individual		Dead individual		Temporarily paralyzed individual	
		No.	%	No.	%	No.	%
50	200	200	100	3	1.50	197	98.50
51	400	400	100	28	7.00	372	93.00
52	400	400	100	69	17.25	331	82.75
53	400	400	100	400	100.00	0	0

From the results stated above, it is easily understood that of three stages of development, the adults are the most resistant to heat, the pupae being next, and the larvae the least, so far as they are free from rice kernels. However, the difference in resistance to heat between the last two is not so significant. And moreover, some allowance must be made in these connections since the pupae and larvae that were taken out of rice kernels are already in abnormal conditions on whose account some degree of mortality may be brought about.

3. *Temporary Paralysis.*

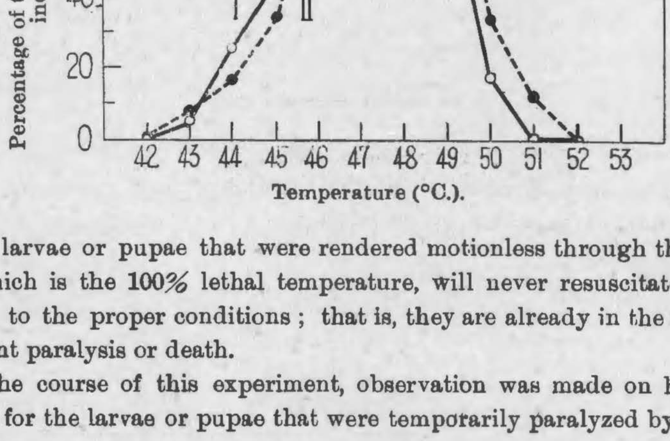
As well as the adult weevils, the larvae and pupae that were hardened by heat will resuscitate either normally or temporarily according to the intensity of paralysis. The relation between the percentage of temporarily paralyzed individuals and the temperature is graphed in Fig. II, being represented by an apparent normal curve. As is evident in this graph, the highest percentage is given at 47°C. where the number of motionless individuals reaches 100%. In other words, most of the individuals, irrespective of whether larvae or pupae that were hardened by their contact to the temperature of 47°C. will come to life when returned to the favourable conditions.

Fig. II.

Relation between the Percentage of Temporarily Paralyzed Individuals and the Temperature.

I. Larva.

II. Pupa.



The larvae or pupae that were rendered motionless through the exposure to 52°C. which is the 100% lethal temperature, will never resuscitate even though returned to the proper conditions ; that is, they are already in the state of either permanent paralysis or death.

In the course of this experiment, observation was made on how long it is required for the larvae or pupae that were temporarily paralyzed by heat to come to life under the favourable conditions (26°±3°C., 70-90% r. h.). The results are shown in Table 4.

Table 4.

Days Required for Larvae or Pupae to Recover from Heat Paralysis.

Temperature that caused paralysis (°C.)	No. of larva recovered on each day after treatment							Mean days required for larva to recover	No. of pupa recovered on each day after treatment							Mean days required for pupa to recover
	1st	2nd	3rd	4th	5th	6th	7th		1st	2nd	3rd	4th	5th	6th	7th	
53	0	0	0	0	0	0	0	—	0	0	0	0	0	0	0	—
52	0	0	0	0	0	0	0	—	0	0	0	1	0	0	0	4.0
51	0	0	2	1	0	0	0	3.3	1	34	9	4	0	0	0	2.3
50	1	8	25	21	11	2	0	3.3	30	24	38	25	16	6	0	2.9
49	76	161	29	3	0	0	0	1.9	138	145	41	5	2	0	0	1.8
48	212	121	27	7	0	0	0	1.5	319	50	11	3	2	0	0	1.2
47	213	139	13	0	0	0	0	1.5	337	37	12	1	0	0	0	1.1
46	302	34	1	0	0	0	0	1.1	317	4	0	0	0	0	0	1.0
45	163	13	0	0	0	0	0	1.1	121	6	0	0	0	0	0	1.0
44	84	0	0	0	0	0	0	1.0	67	0	0	0	0	0	0	1.0
43	19	1	0	0	0	0	0	1.1	31	0	0	0	0	0	0	1.0
42	0	0	0	0	0	0	0	—	5	0	0	0	0	0	0	1.0

From the Table, it is obvious that the temporary paralysis in larvae or pupae occurs between 42°C. and 52°C. and, moreover, that the higher the temperature to which they were exposed, the time required for resuscitation becomes longer, that is to say, the intensity of paralysis becomes severer. The time required for recovery is approximately 1, 2 and 3 days when the temperatures which caused heat paralysis are 44°C. or lower, 49°C., and 50°C. respectively.

As is seen in Table 4, there were a few individuals that came to life in 6 days. As far as the experiment goes, none was resuscitated in 7 days or more, but under different conditions, it might be probable that the longer period would be required before recovery.

The results stated above indicate that the duration of heat paralysis in insects, though fairy short as compared with that of cold paralysis, is not necessarily so short as has been believed up to date *.

III. Lethal Effects of Heat upon Larvae and Pupae.

1. *True Resistance of Larvae and Pupae to Heat.*

In order to learn the true resistance, larvae and pupae taken out of the rice kernels were suddenly exposed to thirteen kinds of high temperature ranging

* The aestivation which comes into question in reference to heat paralysis is not considered here but left for further investigations.

from 40° to 100°C. The length of exposure necessary to kill 100% of naked larvae or pupae was determined for each temperature. The results are shown in Table 5.

Table 5.

Relation between the Length of Exposure Required to Kill All the Naked Larvae or Pupae and the Temperature.

Temperature (°C.)	Length of exposure	Larva			Pupa		
		No. tested	No. dead	% dead	No. tested	No. dead	% dead
100	20 sec.	60	41	68.3	50	44	88.0
	25	60	50	98.3	50	50	100.0
95	25 sec.	50	39	78.0	50	43	86.0
	28	50	50	100.0	50	50	100.0
90	28 sec.	50	32	64.0	50	45	90.0
	30	50	50	100.0	50	50	100.0
85	32 sec.	50	49	98.0	50	48	98.0
	35	50	50	100.0	50	50	100.0
80	35 sec.	100	94	94.0	100	97	97.0
	37	50	50	100.0	50	50	100.0
75	40 sec.	80	77	96.3	70	66	94.3
	45	70	70	100.0	70	70	100.0
70	50 sec.	40	37	92.5	40	39	97.5
	60	50	50	100.0	50	50	100.0
65	1 min. 10 sec.	50	30	60.0	50	38	76.0
	1 20	70	70	100.0	80	80	100.0
60	1 min. 40 sec.	60	47	78.3	60	53	88.3
	1 50	70	70	100.0	70	70	100.0
55	3 min.	80	77	96.3	80	72	92.5
	4	70	70	100.0	80	78	97.5
	5	60	60	100.0	60	60	100.0
50	20 min.	120	117	97.5	90	88	97.8
	25	120	120	100.0	120	120	100.0
45	8 hours	228	213	94.9 *	190	189	99.4 *
	10	220	220	100.0	210	210	100.0
40	2 days			—	140	140	100.0
	3	219	171	78.0 *	—	—	—
	4	147	140		—	—	—
	5	208	208		—	—	—

* These are an average of mortalities obtained in several tests and are not to be calculated directly from the figures in this Table as the numbers employed in each test differed to some extent.

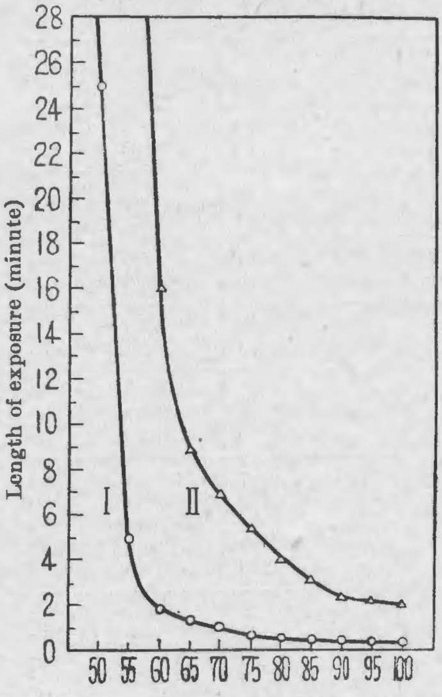
Here the mortality (% dead) is given by an average of 5 to 10 tests for each lot. The number of individuals used in one test varieds from 10 to 50, being more at lower temperature. Hardened individuals that had failed to come to life within a week were regarded as dead.

According to Table 5, it is evident that the length of exposure required to kill 100% of naked larvae or pupae, is shorter as the temperature is higher. The relation between them is represented by the curve as is graphed in Fig. III which is quite similar to the 100% lethal curve of adult weevil. This means that there is no fundamental difference in resistance among adult, larva and pupa.

As is obvious in this Table, no difference in the length of exposure necessary to result in 100% mortality was found between larvae and pupae at all temperatures tested except 40°C. where the latter is far less resistant than the former. This fact may be explained by the following presumption ; that is, the indirect effect of heat which operates through the loss of body water on the part of insects, plays more important role than the direct effect at such a comparatively low temperature as 40°C. where the long exposure is required, and that, there might be considerable difference in rate of losing body water between larvae and pupae.

Fig. III.

100% Lethal Curve of Larvae.



I. Naked larvae.
II. Larvae within kernel.

2. *Apparent Resistance of Larvae and Pupae to Heat.*

For practical purposes it is necessary to know the resistance of larvae or pupae within kernels as they are found in nature. So they were suddenly exposed to high temperatures in the same manner as stated above, and the length of exposure required to get full mortality was observed for each temperature.

The results of experiments are shown in Table 6, in which the mortality is also given by an average of results of 4 - 12 tests for each exposure. About 50 to 100 kernels, each of which containing a larva or pupa within, were used in each test.

Table 6.

Relation between the Length of Exposure Required to Kill All the Larvae or Pupae within Rice Kernel and the Temperature.

Temperature (°C.)	Length of exposure	Larva			Pupa		
		Mortality %	No. tested*	No. of test repeated	Mortality %	No. tested*	No. of test repeated
100	1 min. 45 sec.	98.8	278	6	97.7	179	6
	2 0	99.4	241	5	100.0	147	5
65	2 min. 0 sec.	97.6	227	5	99.3	159	5
	2 15	100.0	192	4	100.0	113	4
90	2 min. 15 sec.	96.1	195	4	91.6	138	4
	2 30	100.0	226	4	100.0	131	4
85	3 min. 0 sec.	95.2	213	4	97.1	137	4
	3 15	99.6	362	5	100.0	106	5
80	3 min. 30 sec.	97.9	346	6	98.3	154	6
	4 0	100.0	245	4	100.0	88	4
75	5 min. 0 sec.	98.2	324	5	99.3	100	5
	5 30	99.1	323	5	100.0	99	5
70	6 min.	96.5	289	5	96.4	119	5
	7	100.0	215	4	100.0	105	4
65	8 min.	99.4	264	4	98.9	99	4
	9	100.0	310	4	100.0	69	4
60	14 min.	94.6	453	9	96.2	155	8
	16	100.0	279	6	100.0	127	6
55	40 min.	91.5	414	7	96.7	325	7
	45	100.0	315	5	100.0	127	4
50	1 hr. 40 min.	52.5	239	5	70.4	149	5
	2 hr.	99.7	342	7	100.0	271	7
45	14 hr.	89.2	500	10	97.1	431	9
	16	100.0	505	9	100.0	361	9
40	2 days	—	—	—	60.0	126	4
	3	—	—	—	100.0	239	4
	4	63.8	231	4	100.0	106	4
	5	98.1	859	12	—	—	—

* 20 - 50 individuals were used in each test.

From the results represented in Table 6, 100% lethal curve is graphed as is shown in Fig. III which does not show any difference with that of naked larvae or pupae but for the fact of comparatively long exposure is required at every temperature. In this case also, any difference in resistance between larvae and pupae can not be seen at every temperature except at 40°C. where the pupae are less resistant than larve.

When the resistance of adult weevil is compared with that of larva or pupa, a very interesting fact may be found. That is to say, when the materials are free from the rice kernels, the adult is more resistant than the larva or pupa at all temperatures except 40°C. where the situation reverses itself; on the contrary, when they are within kernels, the latter two become more resistant than the former. With regard to the reason of this fact, nothing is known though it may be supposed that the economy of body water might be involved in the phenomenon.

As is enumerated in Report I, there are several studies on the resistance of adult weevils, but the experiments which have been conducted with special reference to larvae or pupae are so scarce that few data are here available. GROSSMAN (1931) reported that all the stages of insects affecting stored corn, succumbed at the exposure to 42°C. for 200 hours and to 50°C. for one hour. According to DEAN (1911), all the insect pests in the mill may be killed by the contact to 44.4°C. for 12 hours. These results appear not to stand against the authors' as far as allowance is made for the difference in methods of experiment.

3. *Ratio of Prolongation in Length of Exposure.*

The ratio of prolongation in length of exposure can be calculated from the following formula:

$$R=\frac{K}{N}$$

where

R : ratio of prolongation.

K: length of exposure required to kill 100% of larvae or pupae within kernel.

N : length of exposure required to kill 100% of naked larvae or pupae.

The ratio of prolongation calculated from it is given in Table 7.

From this ratio it can be seen how much the resistance is increased when larvae or pupae are protected by the wall of kernel. As there is no difference in ratio of prolongation between larva and pupa, discussion shall be made mainly on the data obtained with reference to larvae.

The relation between the ratio of prolongation and the temperature is graphed in Fig. IV which suggests that the mechanism of lethal action of heat may differ at least in part with the degree of temperature.

From Fig. IV, it can be generalized that the ratio of prolongation is low (1.3 - 1.6) between 40° - 45°C and high (8.7 - 11.3) between 55° - 60°C., reaching maximum at 55°C. and comparatively invariable (4.8 - 7.3) at the temperatures above 60°C. though it tends to diminish gradually as the temperature rises. Similar tendency had been observed with regard to the adult weevil.

Generally speaking, the ratio of prolongation in larvae or pupae which varies from 1.3 to 11.6 is higher than that of adult weevils which is within the limits of 1.8 - 5.1. This means that the resistance of larvae or pupae is increased more by the protection of kernel wall than adult weevils.

4. *Resistance of Larvae with Reference to their Degree of Development.*

It has been proved with same species of insects that the young larvae are less resistant to heat than the old ones. Therefore this would be the case with regard

Table 7.

Ratio of Prolongation* in Length of Exposure.

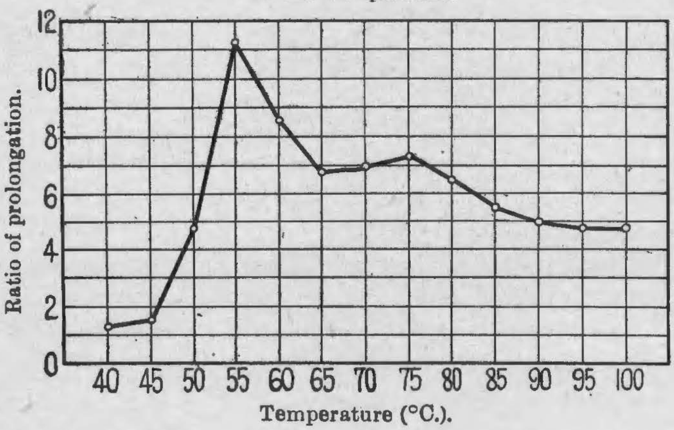
Temperature	Larva		Pupa	
	Necessary prolongation in exposure**	Ratio of prolongation	Necessary prolongation in exposure**	Ratio of prolongation
°C	hr. min. sec.		hr. min. sec.	
100	95	4.8	95 95	4.8 4.8
95	1 47	4.8	1 47	4.8
90	2	5.0	2	5.0
85	2 40	5.6	2 40	5.6
80	3 23	6.5	3 23	6.5
75	4 45	7.3	4 45	7.3
70	6	7.0	6	7.0
65	7 40	6.8	7 40	6.8
60	14 10	8.7	14 10	8.7
55	41	11.3	40	9.0
50	1 35	4.8	1 35	4.8
45	6	1.6	6	1.6
40	24	1.3	24	1.5

* Ratio of length of exposure required to get 100% mortality in larvae or pupae within kernel to that in naked ones.

** Difference in length of exposure necessary to get 100% mortality between larvae or pupae within kernel and naked ones.

Fig. IV.

Ratio of Prolongation in Length of Exposure in Relation to the Temperature.



to the rice weevil. However, the apparent increased resistance of the larvae by the protection of kernel must be of something another.

In this experiment, the rice kernels which contained larvae of various degrees of development were exposed to 60°C. for ten minutes. The kernels thus treated were broken after the lapse of 24 hours to take out the larvae. The larvae were divided into two groups according to their degree of development, one consisting of those in first and second instars and the other third and fourth. And the mortality was inquired for both groups. Here the instar of larvae was determined by the breadth of head. From the frequency curve, it was observed that the breadth of 0.45 mm. separates the second instar from the third. According to the results obtained by Dr. HOZAWA (1927), in second instar the head measures 0.30 - 0.32 mm. in breadth and in third, 0.44 - 0.48 mm. As compared with his results, the authors' materials are somewhat larger in size.

The results of experiment are shown in Table 8. From this, it can be seen that the mortality of young larvae (1st and 2nd instar) is 81 - 86% while that of old ones (3rd and 4th instar) is 63 - 72% ; the former being more resistant than the latter so far as they live within rice kernel. This seems to be attributable to the fact that the young larvae are protected by the comparatively thicker wall of kernel which serves as an obstacle to the penetration of heat. Consequently, the young larvae which are tunnelling through the outer part of kernel are as easily susceptible to heat as old ones.

Table 8.

Mortalities of Young and Grown Larvae that were Exposed to 60°C. for Ten Minutes.

Lot	No. alive	No. dead	Mortality %	Date of exp't.
Grown larva	31	187	85.78	VI/28
	44	183	80.62	VI/30
Young larva	9	23	71.88	VI/28
	11	19	63.33	VI/30

IV. Discussion.

1. *Variation in Resistance to Heat.*

It has been pointed out in many places that the relation between the mortality and the temperature is represented by the S-shaped curve which is the result of individual variations in resistance to heat.

When the frequency (in %) of lethal individuals which can be calculated from Table 1 and 2, is plotted against the temperature, a curve which is moderately asymmetric though almost normal is obtained as is graphed in Fig. V.

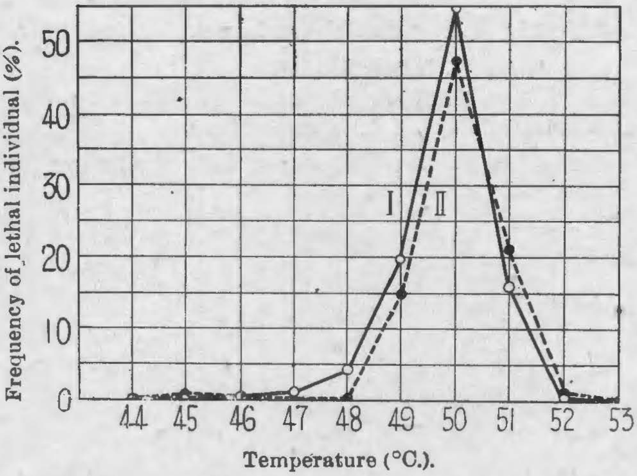
By the general survey over the data obtained in these series of experiment, it will be ascertained that the range of variation in length of exposure which is fatal to individual rice weevil at each temperature becomes smaller as that temperature is higher.

Fig. V.

Frequency of Lethal Individuals at High Temperatures.

I. Larvae.

II. Pupae.



2. Iso-Lethal Curve.

There have been many studies on the thermal death of living forms, in which Q_{10} (VAN'T HOFF), μ (ARRHENIUS) and m (PORODKO) etc. were proposed as a temperature coefficient which indicates the relationship between the life process and the temperature. Now, the law that rules the phenomenon of thermal death in rice weevil must be investigated on the basis of data obtained in these experiments. Hereafter the discussion will be advanced exclusively on the results with larvae, because the pupae show no fundamental difference with them.

For the first place, it can be supposed that the iso-lethal curve could not be represented by only one formula throughout the wide range of temperature tested. Because, as is pointed out, the lethal actions of heat upon insects may operate through different mechanisms with temperature. Taking these views into consideration, the data in Table 5 will be examined. As a result, the 100% lethal curve with reference to naked larvae was proved to be represented by the following formula which PORODKO (1926) had presented as to the lethality of heat to plant seeds.

$$Z = \frac{A}{t^m}$$

where

Z: length of exposure necessary to obtain 100% mortality (in minute).

t: degree of temperature.

A, m: constants.

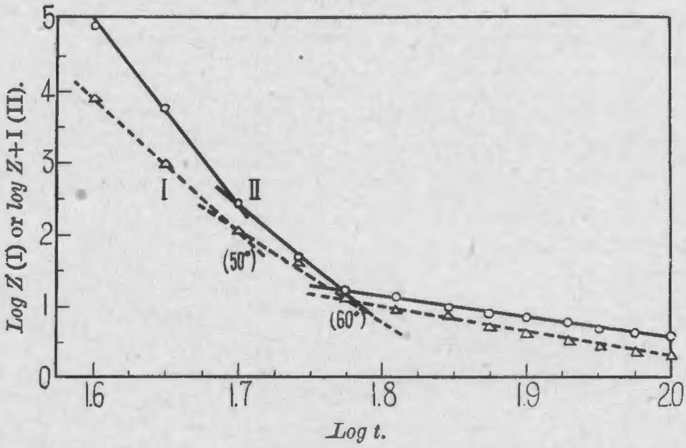
As is apparent from this formula, when *log Z* is plotted against *log t*, a straight line will be had. According to the results of this experiment, three lines instead of one, were obtained as are graphed in Fig. VI. Consequently, the iso-lethal curve must be considered seperately in three ranges of temperature, namely 40° - 50°, 50° - 60° and 60° - 100°C.

Fig. VI.

Three Lines that show the Relation between *log Z* and *log t*.

I. Larvae within kernel.

II. Naked larvae.



The values of constants *A* and *m* calculated by means of least square method for each temperature are given as follows:

Range of temperature	40° - 50°C.	50° - 60°C.	60° - 100°C.
A	10472×10^{44}	13804×10^{26}	188020
m	27.46	16.88	2 85

Therefore the 100% lethal curve can be represented by the following equations.

40° - 50°C. $Z = \frac{10472 \times 10^{44}}{t^{27.46}}$

50° - 60°C. $Z = \frac{13804 \times 10^{26}}{t^{16.88}}$

60° - 100°C. $Z = \frac{188020}{t^{2.85}}$

Comparison of *Z* values calculated from these formulae with those measured in experiment is made in Table 9. From this it can be said that the difference between them is considerably small though it tends to become greater at lower temperatures.

It is evident in Fig. VI that the 100% lethal curve of larvae within kernel may as well be represented by this formula as that of naked larvae. Equations of the curve induced in the similar manner are as follows:

$$40^\circ - 50^\circ C. \quad Z = \frac{38460 \times 10^{20}}{t^{13.08}}$$

$$50^\circ - 60^\circ C. \quad Z = \frac{21565 \times 10^{16}}{t^{10.75}}$$

$$60^\circ - 100^\circ C. \quad Z = \frac{15242 \times 10^{4}}{t^{3.96}}$$

Table 9.

Comparison of Calculated Z* with the Results of Experiment.

Temperature (°C.)	Z measured in min.	Z calculated in min.	Difference in min.
100	0.4166	0.3753	0.0413
95	0.4666	0.4358	0.0308
90	0.5000	0.5073	—0.0073
85	0.5833	0.5977	—0.0144
80	0.6166	0.7089	—0.0923
75	0.7500	0.8519	—0.1019
70	1.0000	1.0352	—0.0352
65	1.3333	1.2797	0.0536
60	1.8324	1.6130	0.2194
60	1.8320	1.3430	0.4890
55	5.0000	5.8750	—0.8750
50	25.0000	28.9730	—3.9730
50	25.0000	23.2000	1.8000
45	600.0000	425.6000	175.0000
40	7200.0000	10690.000	—3490.0000

* Z: Length of exposure necessary to get 100% mortality.

Some earlier workers supposed that the iso-lethal curve might take the form of rectangular hyperbola. According to the results of authors', 100% lethal curve may also be represented by the following formula, so far as the temperature is within the limits of 60°C. to 100°C.

$$Y(X-a)=K$$

where Y: length of exposure.
X: temperature.
a, K: constants.

However, it never holds good at lower temperatures than 60°C.

V. Summary.

In this report, the resistance of larvae and pupae of the rice weevil to heat was studied. The followings are the abstracted results.

1. When naked larvae or pupae were exposed to the temperature rising at a rate of 0.7°C. per minute and maintaining the aimed temperature for 5 minutes, the hardened individuals first appeared at about 42°C. and reached 100% at 47°C. Similarly, the dead individuals appeared at 43°C. and reached 100% at 52°C. Adult weevils treated in the same manner were all killed at 53°C.

2. The relation between the percentage of the motionless individuals and the temperature is represented by an S-shaped curve. The same was also true with the relation between the mortality and the temperature.

3. When heated in the method stated above, the pupae seemed to show somewhat greater resistance than larvae though not so significant.

4. The temporary paralysis in larvae or pupae may be brought about by the contact to the temperature ranging from 42°C. to 52°C. And the time required for them to recover becomes longer as the temperature that caused heat paralysis in them is higher. It was 1, 2 and 3 days on the average when the temperature is respectively 44°C. or lower, 49°C., and 50°C.

5. The lengths of exposure required to kill 100% of larvae or pupae either naked or within kernel were determined for the temperature ranging from 40°C. to 100°C. The 100% lethal curve shows no difference in shape with that of adult weevils.

6. It was proved that the 100% lethal curve may be represented by the formula which Porodko had presented, that is $Z = \frac{A}{t^m}$.

But the constants A and m take different values according to three ranges of temperature, namely 40° - 50°, 50° - 60°, and 60° - 100°C.

7. The larvae and pupae were inferior in true resistance, but superior in apparent resistance to adult weevils. In these connections, the economy of body water is seemed to play an important role.

8. Generally speaking, the ratio of prolongation in length of exposure is low (1.3 - 1.6) at the temperature between 40° - 45°C. and high (8.6 - 11.3) between 55° - 60°C., reaching maximum at 55°C. and medium (4.8 - 7.3) at temperatures above 60°C. though it tends to decrease gradually as the temperature rises. This fact suggests that the lethal effects of heat should operate at least in part through different mechanisms, depending upon the degree of temperature.

9. The young larvae within kernel were more resistant to heat than the old ones regardless of their true resistance. This seems to come from the fact that the former is protected by the thicker wall of kernel.

10. The frequency of lethal individuals which appear at the exposure to every high temperature tested, is distributed almost normally.

The range of variation in length of exposure necessary to be fatal to an individual weevil for each temperature, becomes smaller as that temperature is higher.

VI. Literature.

(1) Dean G. A., Heat as a means of controlling mill insects. Jour. Econ. Entom., 4 : 142 - 161, 1911.

(2) Goodwin, W. H., Some factors affecting results in the use of high temperature for the control of insects injuring cereal products. Jour. Econ. Entom., 7 : 313 - 322, 1914.

(3) Grossman, E. F., Heat treatment for controlling insect pests of stored corn. Bull. Florida Agric. Expt. Sta., No. 239, 24 p., 1931.

(4) Hozawa, S., Observations on the rice weevil, *C. oryzae* L. Annot. Zool. Japon., 12 : 25 - 38, 1927.

(5) Przibram, H., Temperatur und Temperatoren im Tierreiche. Leipzig und Wien, 1923.

(6) Tsuchiya, T., Experimental studies on the resistance of the rice weevil, *C. oryzae* L., to heat. I. Lethal effect of heat upon the adult weevils. Ber. Ōhara Inst. landwirt. Forsch., 9 : 170 - 190, 1943.

(7) Yagi, N. and T. Gamo, Temperature and living matter. (In Japanese). Tokyo, 1942.