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STUDIES ON FRUIT RESPIRATION.

I. The Effect of Temperature on the Respiration of Fruits.

II. The Effect of Picking on the Rate of Evolution of Carbon Dioxid by Peaches.

III. The Rate of Accumulation of Heat in the Respiration of Fruit Under Adiabatic Conditions.

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LETTER OF TRANSMITTAL.

Sir: I have the honor to submit for your approval three studies on fruit respiration made by H. C. Gore of this bureau in cooperation with the Bureau of Plant Industry. Mr. William A. Taylor, acting chief of that bureau, has been in close touch with the work, making suggestions from time to time which have increased its scope and usefulness. I recommend that this manuscript be published as Bulletin No. 142 of the Bureau of Chemistry.

Respectfully,

H. W. Wiley,
Chief of Bureau.

Hon. James Wilson,
Secretary of Agriculture.

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ILLUSTRATIONS.

STUDIES ON FRUIT RESPIRATION.

I. EFFECT OF TEMPERATURE ON THE RESPIRATION OF FRUITS.

INTRODUCTION.

The literature on the effect of temperature on the respiration of plants is well covered up to the year 1905 by the review of Czapek,[1] who notes that de Saussure and his predecessors were well acquainted with the fact that a rise in temperature increases both the rate of absorption of oxygen and the rate of evolution of carbon dioxid. Van't Hoff [2] early noticed that the respiration of plants followed the empirical rule that the rate increases two or three times for each rise of 10° C.[3] Important studies were published in 1905 by Miss Matthaei [4] on the effect of temperature on the respiration and assimilation of leaves, and Kuyper [5] has recently published results on the effect of temperature on the respiration of seedlings. But little work has been reported in the literature on the respiration of fruits. The investigations of Gerber [6] showed that the rate greatly increased on warming. Bigelow and Gore [7] found that the formation of carbon dioxid by apples was much more rapid at cellar temperatures than in storage at 0° C., and F. W. Morse [8] confirmed these results and showed "that at summer temperatures apples will undergo respiratory metabolism from four to six times as rapidly as in modern cold storage."

The work herein reported was undertaken to obtain more information along this line, which is of special value at this time, when such rapid advances are being made in the field work on the transportation and storage of fruit. The plan followed consisted, in brief, in determining the rate of evolution of carbon dioxid from fruit kept in the dark at different temperatures and supplied freely with air.

[1] Biochemie der Pflanzen, 1905, 2 : 397.
[2] Études de dynamique chemique, 1883.
[3] This point is further discussed on p. 28.
[4] See p. 28.
[5] Kon. Akad. van Weten Amsterdam, 1909, 12 (1) : 219; and Recueil des Travaux Botan. Néerlandais, 1910, 7 : 131.
[6] Ann. des sciences naturelles, 1896, (8), 4 : 1.
[7] U. S. Dept. Agr., Bureau of Chemistry, Bul. 94.
[8] J. Amer. Chem. Soc., 1908, 30 : 876.

SELECTION AND PREPARATION OF THE FRUIT.

Whenever practicable the variety and locality were selected by Wm. A. Taylor, of the Bureau of Plant Industry, in order that the study should have as direct an application as possible to field work. The fruits so selected came from localities in which the particular variety was grown under typical conditions on a commercial scale. The fruit from the Arlington farm was usually picked from the trees on the day preceding the date of the beginning of the experiments. Except where noted, none of the fruit had been subjected to cold storage or any known condition which could cause abnormality.

Each sample was prepared for the experiment by first eliminating unsound or injured specimens. The sample was then divided into two or more weighed lots for the measurement of the rate of respiration at different temperatures. After weighing, each lot of fruit was kept at the temperature at which it was desired to measure the rate of respiration for several hours or overnight before starting the experiment, in order that it might acquire the temperature of its surroundings. To effect this the fruit was placed either in open baskets beside the desiccators in which it was to be run later, or in the desiccators themselves. In the latter case a rapid current of air was passed through them in such a way that the air surrounding the fruit was continuously renewed. In the case of the small fruits, the greatest care was exercised in selecting and handling them during the operations of weighing and placing in desiccators. The best specimens as far as freedom from any suspicion of spoilage was concerned were selected for the experiment at room temperature, as it was realized that here was the greatest danger of vitiation of the results, owing to the activities of yeasts and other microorganisms. The red raspberries, in particular, were extremely delicate, and it was difficult to avoid breaking them during the necessary handling of the fruits. Similar precautions were necessary in the case of blackberries. With the red and black currants, only berries attached to stems were used, to lessen the chances of deterioration due to the development of microorganisms at the pedicels. At times, in the work on the small fruits, the experiments were run for several days in order to obtain duplicate determinations on the same lot of fruit. In all cases well agreeing duplicates were obtained except where visible deterioration due to spoilage occurred. The first lot of black raspberries had perceptibly molded at the close of the period of measurement in the desiccator kept at room temperature, and accordingly, a few days later, a second sample of fruit from the same patch was run. This sample also molded very slightly. It is probable that, in both cases, increases of carbon dioxid due to activities of microorganisms were very small. The huckleberries and the wild blackberries were obtained

from the local market, and no reliable data as to place of origin could be obtained. The huckleberries were identified by F. V. Coville, of the Bureau of Plant Industry.

The peaches from Georgia had been shipped in refrigerator cars and were cold when received. The data for the Carman variety were obtained first on a sample of hard-green fruit. Weighed lots of the same sample of peaches were allowed to ripen at room temperature and were then examined to determine whether there were differences in the rate of respiration between the green and the ripened fruit. The locally grown peaches, Champion, Connett, and Elberta, were picked when hard-ripe and well colored.

The lemons were divided into two lots, the fruit which was still partly green and that which was fully yellowed, and examined separately. Both the oranges and lemons were freshly picked fruit sent by express from California.

The pineapples and Japanese persimmons were well colored but firm; the latter did not soften while under observation. The mangos were highly colored and eating-ripe.

The apples were all recently picked, the two summer varieties, Jefferis and Summer Pearmain, having been gathered on the day previous. The three lots of winter apples from California were well colored, freshly picked fruit sent by express.

The four varieties of Vinifera grapes were purchased on the local market, those from California probably having been shipped in refrigerator cars.

Two attempts were made to determine the effect of temperature on the rate of evolution of carbon dioxid from bananas but without success on account of the very rapid acceleration in the rate of evolution of carbon dioxid with ripening. These trials showed that the rate of physiological activity increased greatly even overnight. The effect of temperature on the respiration of bananas will be the subject of further study.

DESCRIPTION OF APPARATUS AND METHODS.

ABSORPTION APPARATUS.

The apparatus used in the measurement of respiration intensity at each temperature is shown in fig. 1. The air entering the desiccator was first drawn through a long tube filled with soda lime to free it from carbon dioxid; it was next passed through a wash bottle containing baryta water and then through a drying tower containing calcium chlorid. The wash bottle was useful in testing the apparatus for tightness and for insuring that the air was properly purified, while the drying tower was used in the measurements at room, ice-box, and cold-storage temperatures, as it was feared that the

use of air nearly or quite saturated with water vapor would cause excessive humidity. The air entered each desiccator near the top and was removed through a delivery tube reaching nearly to the bottom. From the desiccator it was drawn through a Reiset absorption apparatus, then through another wash bottle containing baryta water and to the suction pump. The air current was drawn through at the rate of from 2 to 4 liters per hour.

The desiccators were kept in the dark usually at some distance from their respective sets of purifying and absorption apparatus. The gases were led to and from them in copper tubes (one-fourth
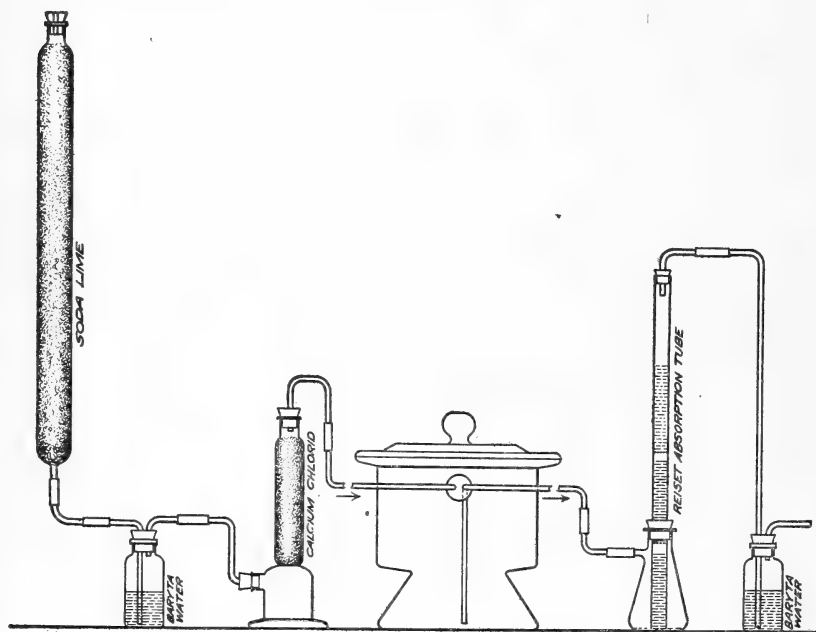
Fig. 1.—Purifying and absorption apparatus.

inch outside diameter and one thirty-second inch wall) which possessed, in addition to the advantage of being infrangible, the property of being easily bent into the required shapes. In all apparatus care was taken to have the ends of the glass or copper tubes come together closely at the joints, and to avoid entirely leading gases in rubber tubes because of the well-known fact that rubber absorbs carbon dioxid selectively.[1] The desiccators were of the tubulated Scheibler pattern, 8 or 10 inches in diameter. No difficulty was experienced in fitting the covers tightly, provided the glass surfaces were plane and finely ground. The two-holed stoppers carrying the tubes were well lubricated with vaseline, forced tightly into place, and tied.

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[1] Morse, H. N., Exercises in Quantitative Chemistry, 1905, p. 77.

TEMPERATURES.

The fruits were usually held at three different temperatures, although at times four were employed and in several cases only two are recorded. The four temperatures were as follows: (1) A cold-storage temperature of about 2° C., which was usually very steady and rarely varied more than 1° during a run. (2) An ice-box temperature of from 7.1° to 12.7° C. The temperature in this case usually rose slowly during a determination as the surface of the ice decreased with melting, and rarely varied more than 2° C. during a determination. (3) Room temperature, which varied according to the season of the year from 20.5° to 31.2° C., but was very steady from day to day, as the darkened cabinet in which the desiccator was kept
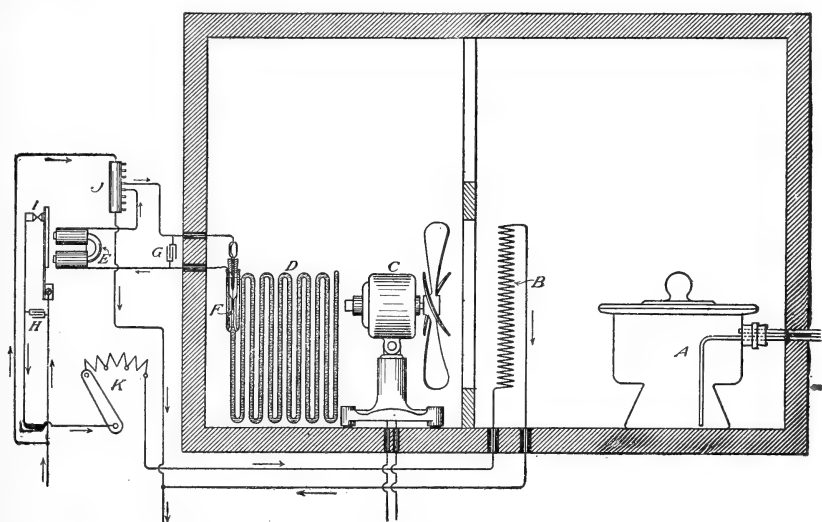
Fig. 2.—Electrically-heated, constant-temperature incubator.

was situated out of the way of drafts. (4) The incubator temperature, from 32.6° to 35.6° C., was automatically regulated and varied at most but 0.2° C. during a determination. The temperatures were taken at the beginning and at the end of a run by reading short corrected thermometers placed in the desiccators among the fruit.

REGULATION OF INCUBATOR.

The incubator in which the fruit was kept when it was desired to measure the respiration at a higher temperature than that of the room consisted of a wooden cabinet with well-fitting doors. The arrangement of the heating device is shown diagrammatically in fig. 2. The incubator was large enough to contain the desiccator, A, an electric fan, C, an electric heating coil, B, a thermostat, D, and various lots of fruit. In planning the method of heating slightly

above the highest room temperature attained during the summer, it was necessary to keep in mind the fact that such an incubator has a small heat capacity and the heater must likewise be of low heat capacity, so that the temperature may cease to rise as soon as the circuit is opened; otherwise the temperature may rise and fall through a wide range.

The heating device, B, was a set of coils taken from an electric toaster. This was placed directly in front of the fan, C, so that the heat as supplied was quickly distributed through the chamber. The thermostat, D, consisted of a long coiled glass tube filled with mercury. It was closed at one end, mounted on a wooden frame not shown, and provided at the other with a simple device for making and breaking a low-tension electric current as the temperature varied. The essential part of the thermostat is shown in detail in fig. 3. While involving nothing new in principle, the arrangement has been found to combine sensitiveness with stability. Electric connection is made with the mercury of the thermostat through the platinum wire A. It is necessary that mercury of high purity be used, that its surface be kept free from dust, and that sparking at the point of contact between the mercury and the platinum wire be reduced to a minimum. The heat was supplied by the 110-volt, direct lighting current which was cut in and out by a telegraph relay, E, actuated by opening or closing the small current at the point of contact in the thermostat.

Two points in the electrical arrangements deserve special mention. First, sparking was avoided in the usual manner by placing condensers G and H across the spark gaps at F and I, respectively. In making and breaking the heating current it was found that if the condenser was too large enough energy was stored in it to cause small sparks when the circuit was closed at the contact points, causing them to adhere at times so that they failed to separate at the pull of the electro-magnet. The condenser finally used for breaking this current consisted of three pairs of plates of tin foil separated by waxed paper. The effective area of each sheet was about 500 square centimeters. The second point is the method of getting the small constant current which is made and broken in the thermostat. This was obtained as a shunt from the 110-volt direct current by using a resistance coil, J, rated at 1,000 ohms, con-

FIG. 3.—Detail of thermostat.

sisting of a coil of wire wound on a porcelain tube over which enamel had been baked, with 8 taps taken off at even points along the tube. The small shunted current used in actuating the relay was taken from two adjacent taps. It was thus at a potential difference of about 11 volts when the resistance coil was connected in the 110-volt circuit.

A rheostat, K, was found useful in regulating the amount of current supplied to the heater. If the amount sent through is but slightly more than sufficient to supply the usual losses of heat from the incubator, the current will be on nearly all of the time and the regulation of the temperature will be very exact. If the room temperature should be considerably lowered, however, sufficient heat would not be supplied. If, on the other hand, much current is used, the heat would be on for but a small fraction of the time, but the temperature would vary within wider limits. It was found well to adjust the rheostat so that the circuit was closed about half the time. The current strength was about 3 amperes.

Except for the thermostat, which should be made by an expert glass worker, the entire outfit may be selected from electrical supplies now on the market.

COLLECTION AND ESTIMATION OF CARBON DIOXID.

As stated on page 8, the air was withdrawn from each desiccator and passed through a Reiset absorption apparatus where the carbon dioxid was quantitatively removed. The Reiset tubes were similar to those used by Reiset [1] and by Brown and Escombe.[2] Each apparatus consisted of a long, wide glass tube fixed vertically in a side-arm flask by a gasket made from a rubber stopper. The tube was 50 cm high and 2 cm in diameter. Platinum disks were fixed at the lower end, 12.5 and 25 cm, respectively, from the bottom. These disks were pierced with fine holes about 0.5 mm in diameter and their edges sealed into the walls of the tube.

When in operation, the absorbing liquid rises in the tube, the air which is then drawn through the lowest disk "rises through the column of liquid in a rapid stream of small bubbles which are broken up and reformed at each of the two succeeding plates, thus producing a very effective 'scrubbing' action." [3]

Generally 100 cc of normal sodium hydroxid were used as the absorbent, but at times double normal alkali was employed. During the early part of the work two Reiset tubes connected in series were used, but later it was found that one was sufficient unless very large amounts of carbon dioxid were to be collected.

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[1] Compt. rend., 1879, **88** : 1007; 1880, **90** : 1144; Hempel, Gas Analysis, 1902, p. 110.
[2] Royal Society, London, Proc. 1905 (B) **76** : 29.
[3] Brown and Escombe, loc. cit., p. 33.

The method of double titration employed by F. W. Morse [1] and
by Brown and Escombe [2] was used, in which phenolphthalein and
methyl orange are employed successively. It was found convenient
to rinse the soda solution into a precipitating jar of about 650 cc
capacity. If much carbon dioxid had collected the volume of the
solution to be titrated was increased considerably by adding water,
and it was found necessary to stir rapidly, and to have the tip of
the burette well down in the solution; these precautions tend to
avoid loss of carbon dioxid due to the presence of local excess of acid.[3]
Normal hydrochloric acid was added until the solution was colorless.
Methyl orange was then added and the titration finished. The
sodium hydroxid solution used contained a small known amount of
carbonate whose value expressed in terms of normal hydrochloric
acid was subtracted from the results of each titration. Küster [4]
has critically reviewed the volumetric methods for the determina-
tion of carbon dioxid. He found that this method of double titra-
tion was faulty on account of the fact that sodium bicarbonate is
faintly alkaline to phenolphthalein, and low results for carbon dioxid
may consequently be obtained. If the titration with hydrochloric
acid is carried to the point where the solution is colorless to reflected
light while still containing a trace of red color when compared with
a control, Küster found that accurate results were obtained, but
notes that the end point is empirical. He states also that methyl
orange is strongly colored by carbon dioxid and the titration with
this indicator should be carried to a *normal* tint, which is defined
as that of an aqueous solution of the indicator, of the same concen-
tration as the one used in the titration, saturated with carbon dioxid.
The writer was not familiar with the work of Küster until the study
was well under way, and it was then considered best not to change
the method. No control was used in judging when the phenol-
phthalein pink disappeared, and the end point was thus essentially
the empirical one described by Küster. The error caused by the
uncertainty of the end point can hardly amount to more than 1
per cent of the amounts of carbon dioxid found. Very accurate
results were obtained by Küster by using the Winkler [5] method in
which solution of barium chlorid is added in excess. The titration
is then made without filtering, using phenolphthalein. This there-
fore appears to be the best volumetric method of determining carbon
dioxid.

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[1] Loc. cit.

[2] Loc. cit.; Royal Society, London, Philos. Trans. 1900, (B) **193** : 289.

[3] Certain minor refinements used by Brown and Escombe in their work on leaves, in which very small amounts of carbon dioxid were estimated (using sodium hydroxid prepared from sodium, using dilute acid in titrating, and taking measures against contamination from the atmosphere of the solutions to be titrated during their transfer from the absorption apparatus), were omitted, as blank determinations were found to give constant results irrespective of slight changes in technique.

[4] Zts. anorg. Chem., 1896, **13** : 127.

[5] Cl. Winkler, Massanalyse; see also Böckmann, Untersuchungsmethoden, pp. 408, 411, and 413; through Küster, loc. cit.

IES-RED CUTHBERT

ADO-2ND.

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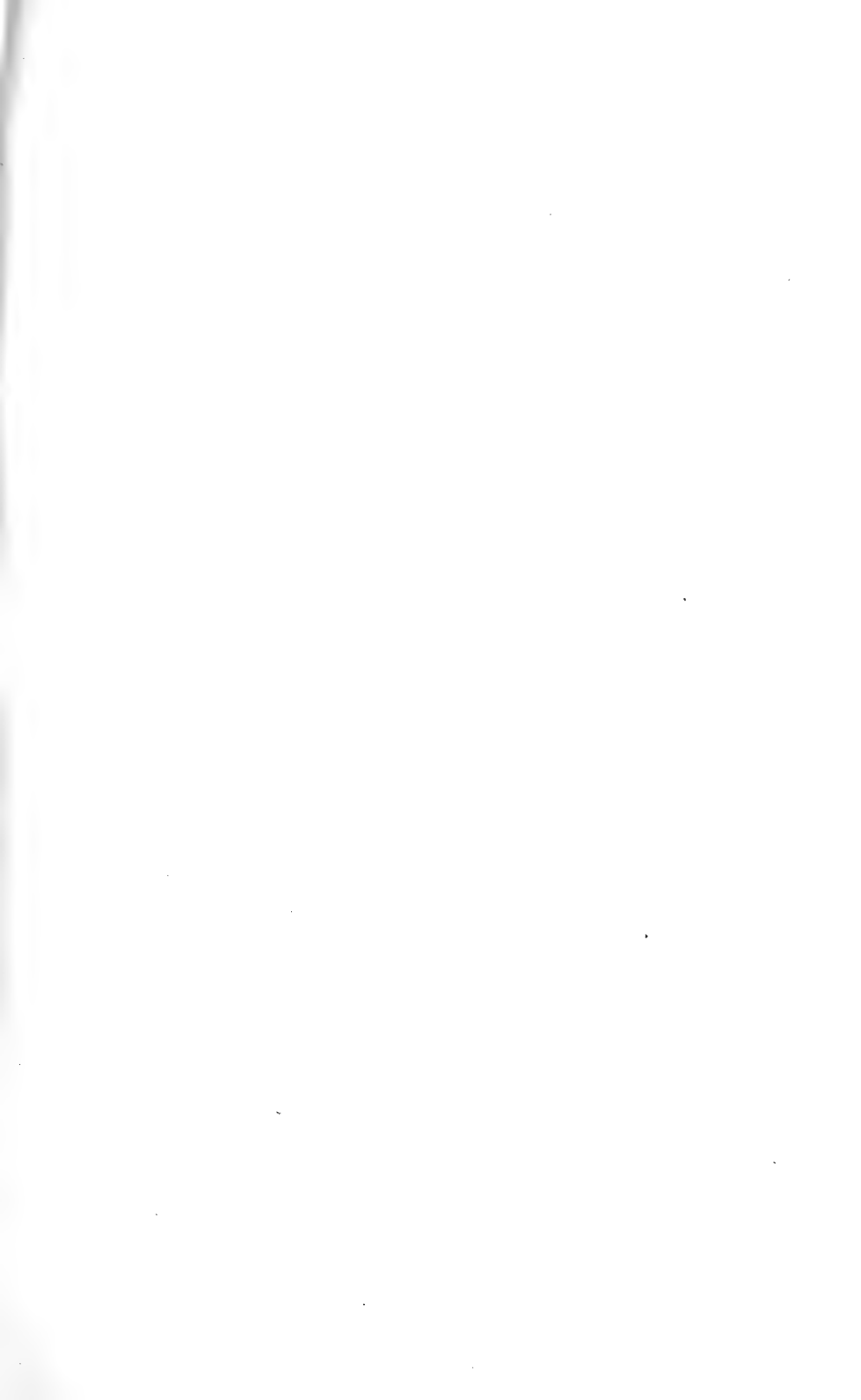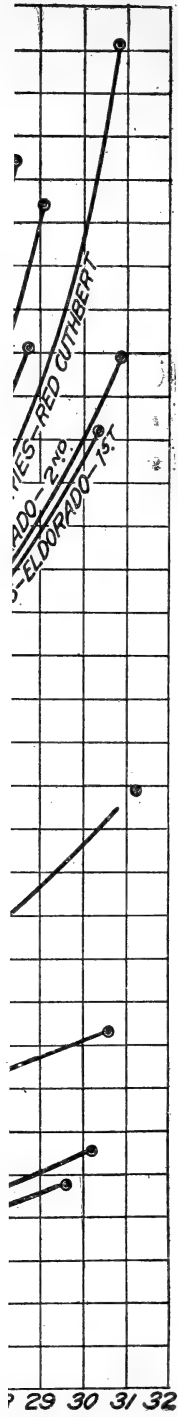
STATEMENT OF RESULTS.

The kind and variety of fruit, the locality where grown, date, weight of fruit used, the interval during which the carbon dioxid was collected, the average temperature during this period, and the carbon dioxid formed expressed in milligrams per kilogram of fruit per hour, are given in Table 1, following. The data have been calculated also in terms of the volume of carbon dioxid per kilogram per hour. The time in hours which will be required for the fruit to give off its own volume of carbon dioxid has been calculated on the assumption that 1 kilogram of fruit occupies 1,000 cc. The results in terms of milligrams of carbon dioxid per kilogram per hour are given graphically in figs. 4 to 8, inclusive. In plotting, curved lines have been used in connecting the several determined points. While straight lines are more commonly used, particularly when but few points are determined, it is believed that the curves show better the constantly accelerated activity as the temperature rises. They were drawn with a spline and spline weights.

TABLE 1.—*Effect of temperature on the rate of respiration of fruits.*

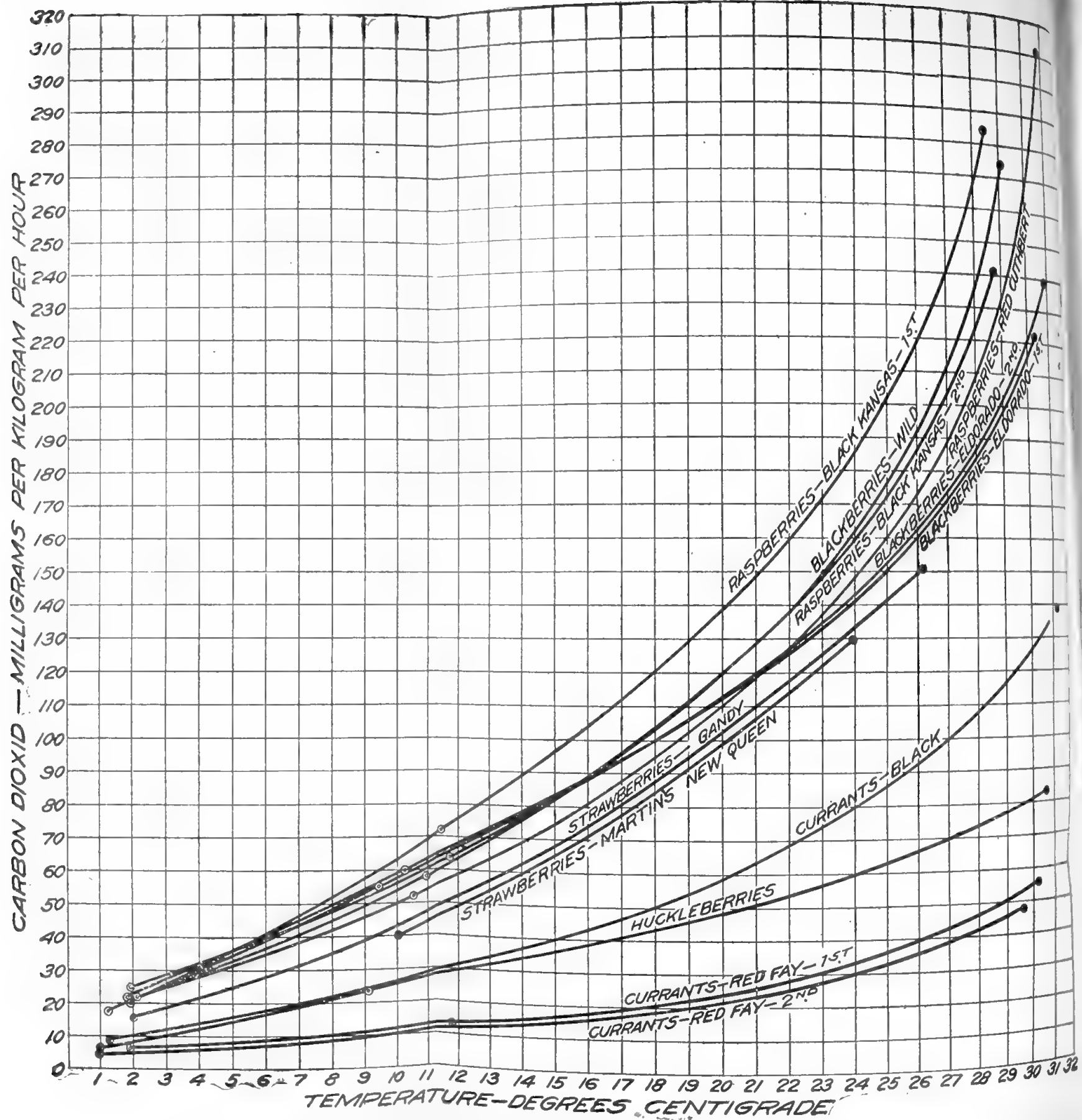| Kind and variety of fruit.	Locality where grown.	Date received.	Weight.	Interval during which carbon dioxid was collected.	Average temperature.	Carbon dioxid.		Time required for fruit to evolve carbon dioxid equal to its own volume.
						Amount (milligrams per kilogram per hour).	Volume (cubic centimeters per kilogram per hour).	
Strawberries:		*1910.*	*Grams.*	*Hours.*	*° C.*			*Hours.*
Martin's New Queen......	Arlington, Va.....	June 10	1,000	18.3	23.9	130	72.0	13.9
				18.3	10.1	41	21.6	46.3
Gandy..................	Washington, D. C.	June 17	1,000	18.0	26.2	151	84.3	11.8
				18.0	10.6	46	24.3	41.2
				20.0	2.0	17	8.7	114.9
Black raspberries:								
Kansas.................	West Falls Church, Va.	June 18	1,000	20.0	28.4	284	159.7	6.3
				20.0	11.4	72	38.2	26.2
				22.0	1.9	20	10.3	97.1
Do.......................	.....do............	June 21	1,000	17.5	28.7	241	135.7	7.4
				17.0	11.7	64	34.0	29.4
				17.5	1.9	25	12.8	78.1
Red raspberries:								
Cuthbert..................	Anne Arundel County, Md.	July 2	1,000	19.5	30.8	311	176.4	5.7
				19.8	10.5	52	27.5	36.4
				20.3	2.1	22	11.4	87.7
Blackberries:								
Eldorado, first day's run..	Maryland.........	July 7	1,000	18.7	30.3	222	125.7	8.0
				18.5	10.2	60	31.7	31.5
				19.5	1.8	22	11.3	88.5
Eldorado, second day's run.	.....do............	July 8	1,000	26.7	30.8	239	135.5	7.4
				25.8	9.4	55	29.0	34.5
				25.3	1.2	*18	9.2	108.7
Wild.....................	....	June 28	1,000	16.8	29.0	274	181.8	5.5
				17.0	10.9	58	30.7	32.6
				17.5	1.9	22	11.3	88.5
Red currants:								
Fay, first day's run.......	New York.........	July 16	1,000	24.1	30.2	56	31.7	31.5
				23.9	11.8	13	6.9	144.4
				24.5	1.8	7	3.4	294.1
Fay, second day's run.....	.....do............	July 17	1,000	24.1	29.6	48	27.1	36.9
				24.1	9.1	10	5.3	188.7
				24.5	0.8	5	2.6	384.6

FIG. 4.—Effect of temperature on the rate of respiration of blackberries, currants, huckleberries, raspberries, and strawberries.

95678°—Bull. 142—11.   (To face page 13.)

STUDIES ON FRUIT RESPIRATION.

TABLE 1.—*Effect of temperature on the rate of respiration of fruits*—Continued.

Kind and variety of fruit.	Locality where grown.	Date received.	Weight.	Interval during which carbon dioxid was collected.	Average temperature.	Carbon dioxid.		Time required for fruit to evolve carbon dioxid equal to its own volume.
						Amount (milligrams per kilogram per hour).	Volume (cubic centimeters per kilogram per hour).	
		1910.	*Grams.*	*Hours.*	° *C.*			*Hours.*
Black currants:								
First day's run............	Geneva, N. Y.....	July 25	1,000	15.6	31.2	139	78.9	12.7
				15.5	11.2	28	14.8	67.6
Second day's run..........	.....do.........	July 26	1,000	24.1	30.9	136	77.1	13.0
				24.1	11.2	29	15.4	64.9
				20.8	1.2	9	4.6	217.4
Third day's run............	.....do.........	July 27	1,000	23.5	30.6	163	92.4	10.8
				23.5	11.2	28	14.8	67.6
				24.2	1.2	9	4.6	217.4
Huckleberries:								
Gaylussacia baccata........	....	Aug. 4	1,000	6.3	30.6	84	47.6	21.0
				6.8	9.1	23	12.1	82.6
				6.6	0.9	7	3.6	277.8
Peaches:								
Carman, hard-ripe.........	Americus, Ga.....	June 27	1,000	17.3	27.2	120	67.2	14.9
				17.5	10.6	20	10.6	94.3
				17.5	1.8	8	4.1	243.9
Carman, ripened..........	.....do.........	June 29	1,000	16.8	29.2	134	75.6	13.2
				17.5	9.9	28	14.8	67.6
				17.8	1.4	11	5.6	178.6
Do.......................	.....do.........	June 30	944	23.8	31.4	134	76.1	13.1
			1,000	24.2	8.8	22	11.6	86.2
			1,000	24.3	0.7	9	4.6	217.4
Hiley......................	Fort Valley, Ga...	July 6	1,000	16.5	29.0	114	75.7	13.2
			1,000	16.8	9.5	19	10.0	100.0
Champion..................	Arlington Farm, Va.	Aug. 20	1,358	42.8	25.7	84	46.8	21.4
			1,306	42.4	7.1	13	6.8	147.1
			1,184	42.9	1.3	7	3.6	277.8
Connett, first day's run....	.....do............	July 22	1,000	23.9	29.0	104	69.0	14.5
			1,000	23.9	10.7	25	13.2	75.8
			1,000	24.3	1.1	7	3.6	277.8
Connett, second day's run.	.....do............	July 23	1,000	47.6	29.6	93	52.5	19.1
			1,000	47.8	11.0	22	11.7	85.5
			1,000	47.5	1.1	6	3.1	322.6
Elberta....................	.....do............	Aug. 30	1,794	16.8	32.6	106	60.5	16.5
			1,806	16.9	26.4	73	40.8	24.5
			1,798	18.8	9.8	19	10.0	100.0
			1,814	18.8	1.2	7	3.6	277.8
Plums:								
Wragg.....................	.....do............	Aug. 25	1,209	21.3	27.4	69	38.7	25.8
			1,209	20.9	12.1	19	10.1	99.0
			1,209	21.3	1.5	6	3.1	322.6
Goff.......................	.....do............	Aug. 10	1,000	28.3	30.7	103	58.4	17.1
			1,000	28.5	8.4	10	5.3	188.7
			1,000	28.5	1.7	6	3.1	322.6
"Damson"	Washington, D. C.	Aug. 23	1,000	23.9	26.1	44	24.6	40.7
			1,000	24.0	10.2	10	5.3	188.7
			1,000	24.6	1.3	5	2.6	384.6
Pears:								
Seckel....................	Takoma Park, Md.	Aug. 22	2,000	20.1	26.3	23	12.8	78.1
			2,000	20.4	7.6	5	2.6	384.6
			2,000	20.3	0.9	3	1.5	666.6
Kieffer...................	Arlington Farm, Va.	Sept. 15	2,014	24.7	34.4	50	28.7	34.9
			2,010	24.7	22.6	19	10.5	95.2
			1,934	24.3	10.9	11	5.8	172.4
			1,906	24.6	2.9	4	2.1	476.2
Apples:								
Jefferis...................	College Park, Md..	Aug. 18	2,024	22.5	27.5	46	25.8	38.8
			2,005	22.5	10.1	13	6.9	144.9
Summer Pearmain........	.....do............	Aug. 19	2,138	23.8	26.6	46	25.7	38.9
			2,145	23.7	8.7	13	6.8	147.1
			2,083	23.5	1.4	4	2.1	476.2
Yellow Bellflower.........	Watsonville, Cal..	Oct. 1	1,847	5.7	34.1	65	37.3	26.8
			1,778	14.7	24.8	30	16.7	59.9
			1,778	14.6	9.7	13	6.9	144.9
			1,999	14.7	2.5	3	1.5	666.6
Red Pearmain.............	.....do............	Oct. 2	1,613	14.8	34.1	50	28.7	34.9
			1,622	14.8	23.0	21	11.6	86.2
			1,603	14.8	10.7	11	5.8	172.4
			1,610	15.0	2.8	4	2.1	476.2
Missouri Pippin...........	.....do............	Nov. 14	1,751	21.3	20.7	29	....	....
			1,613	21.3	10.8	12	....	....
			1,583	21.4	1.9	5	....	....

TABLE 1.—*Effect of temperature on the rate of respiration of fruits*—Continued.

Kind and variety of fruit.	Locality where grown.	Date received.	Weight.	Interval during which carbon dioxid was collected.	Average temperature.	Carbon dioxid.		Time required for fruit to evolve carbon dioxid equal to its own volume.
						Amount (milligrams per kilogram per hour).	Volume (cubic centimeters per kilogram per hour).	
Grapes:		*1910.*	*Grams.*	*Hours.*	*°C.*			*Hours.*
Black Cornichon	California	Oct. 15	1,651	17.7	34.2	46	26.4	37.9
			1,676	24.0	21.3	22	12.1	82.6
			3,457	17.7	11.3	9	4.8	208.4
			3,570	17.7	2.2	3	1.5	666.6
Flame Tokay, first run	Clements, Cal	Oct. 6	1,536	5.3	34.2	57	32.7	30.6
			1,523	5.3	25.9	24	13.4	74.6
			1,539	5.3	11.6	8	4.3	232.6
			1,500	5.7	1.8	5	2.6	384.6
Flame Tokay, second run	.....do	Oct. 6	1,536	17.4	34.2	55	31.5	31.8
			1,523	17.4	26.1	29	16.2	61.7
			1,539	17.4	10.0	7	3.7	270.3
			1,500	17.4	1.8	3	1.5	666.6
"Almeria"	Spain	Dec. 1	1,113	16.0	20.5	17	......	......
			1,113	16.0	10.1	5	......	......
			1,113	21.1	2.9	2	......	......
James	Willard, N. C	Sept. 9	1,056	16.7	34.3	60	34.4	29.1
			1,130	16.8	27.2	33	18.5	54.1
			1,133	16.9	9.3	8	4.2	238.1
			1,138	17.0	2.3	5	2.6	384.6
Delaware	Arlington, Va	Aug. 29	1,224	16.7	34.2	86	49.3	20.3
			1,246	16.6	27.0	48	26.9	37.2
			1,110	23.6	9.8	13	6.9	144.9
			1,087	23.8	1.4	4	2.1	476.2
Concord	Penn Yan, N. Y	Oct. 20	1,240	17.3	34.2	118	67.7	14.8
			1,356	23.2	23.7	60	33.2	30.1
			1,451	20.4	12.7	22	11.7	85.5
			1,214	20.3	2.5	6	3.1	322.6
Niagara	New York	Oct. 21	1,791	17.6	34.2	102	58.5	17.1
			1,714	17.6	22.9	48	26.5	37.7
			1,781	20.2	12.3	14	7.5	133.3
			1,890	21.1	2.4	6	3.1	322.6
Catawba	.....do	Oct. 22	1,613	16.8	34.2	101	57.9	17.3
			1,591	16.8	21.1	32	17.6	56.8
			1,532	16.7	9.5	8	4.2	238.1
			1,530	24.6	2.2	5	2.6	384.6
Oranges:								
Valencia, late	San Dimas, Cal	Aug. 15	2,025	23.1	29.3	23	13.0	76.9
			2,105	23.1	9.0	4	2.1	476.2
			2,226	21.4	1.7	2	1.0	1,000.0
Lemons:								
Eureka, partly green	.....do	Aug. 13	2,004	30.8	29.3	20	11.3	88.5
			2,020	30.8	8.2	3	1.6	625.0
			2,080	31.0	1.7	2	1.0	1,000.0
Eureka, fairly well yellowed.	.....do	Aug. 14	2,005	11.3	28.4	17	9.6	104.2
			2,003	11.4	9.7	4	2.1	476.2
			2,033	11.7	1.7	2	1.0	1,000.0
Pineapples:								
Red Spanish	Viking, Fla	Aug. 3	2,319	18.5	31.2	104	59.0	17.0
			2,479	18.6	11.1	12	6.4	156.2
			2,536	18.5	1.2	7	3.6	277.8
Smooth Cayenne, first day's run.	West Palm Beach, Fla.	July 28	1,754	25.8	30.1	60	33.9	29.5
			1,652	25.7	11.0	8	4.2	238.1
			1,017	26.3	2.5	5	2.6	384.6
Smooth Cayenne, second day's run.	.....do	July 29	1,754	21.9	30.0	50	28.3	35.3
			1,652	21.9	8.6	7	3.7	270.3
			1,017	22.0	2.4	6	3.1	322.6
Mangos:								
Turpentine	Miami, Fla	Sept. 10	930	23.8	34.4	192	110.2	9.1
			794	23.8	27.2	123	68.9	14.5
			955	23.3	8.2	18	9.4	106.4
			873	22.6	2.3	6	3.1	322.6
Japanese persimmons:								
Hachiya	Dinsmore, Fla	Sept. 23	828	23.9	35.6	44	25.3	39.5
			843	23.9	24.0	25	13.9	71.9
			953	23.5	10.3	10	5.3	188.7
			892	23.6	2.9	3	1.5	666.6
Tane-nashi	.....do	Sept. 24	1,044	42.4	35.6	[1] 31	17.9	55.9
			1,146	42.4	25.0	34	18.9	52.9
			1,200	42.4	8.5	6	3.2	312.5
			1,054	42.3	2.8	2	1.0	1,000.0

[1] Two days later the rate decreased to 23 mg per kilogram per hour.
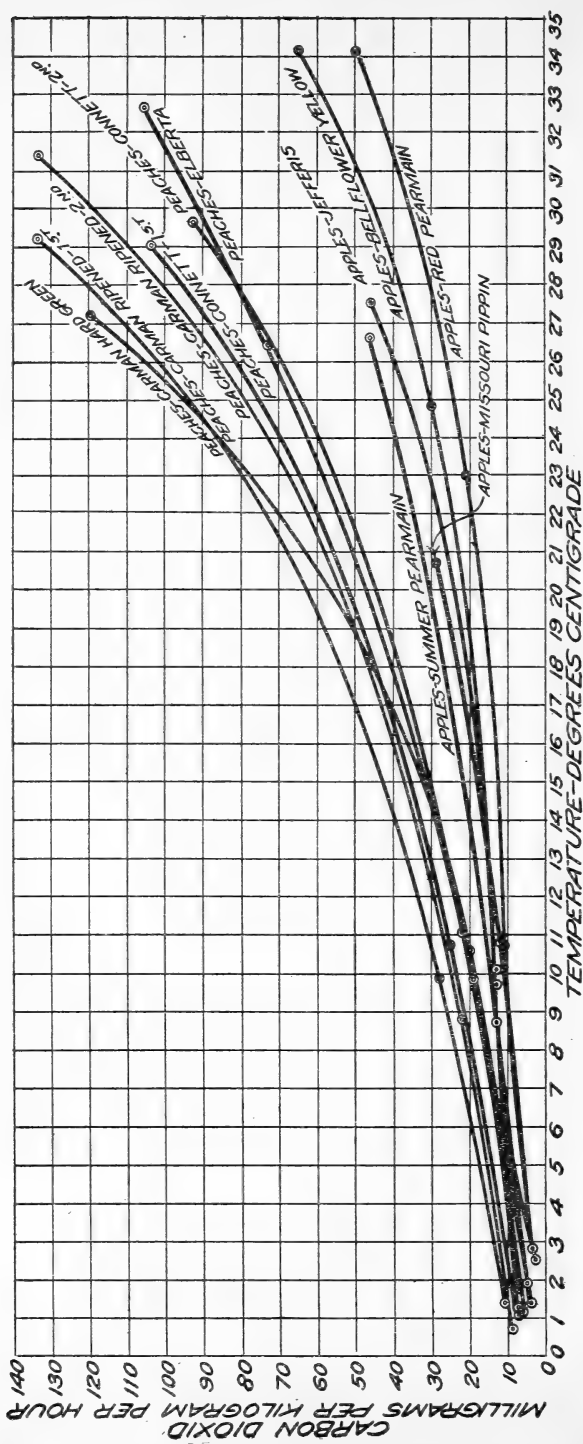
FIG. 5.—Effect of temperature on the rate of respiration of peaches and apples.
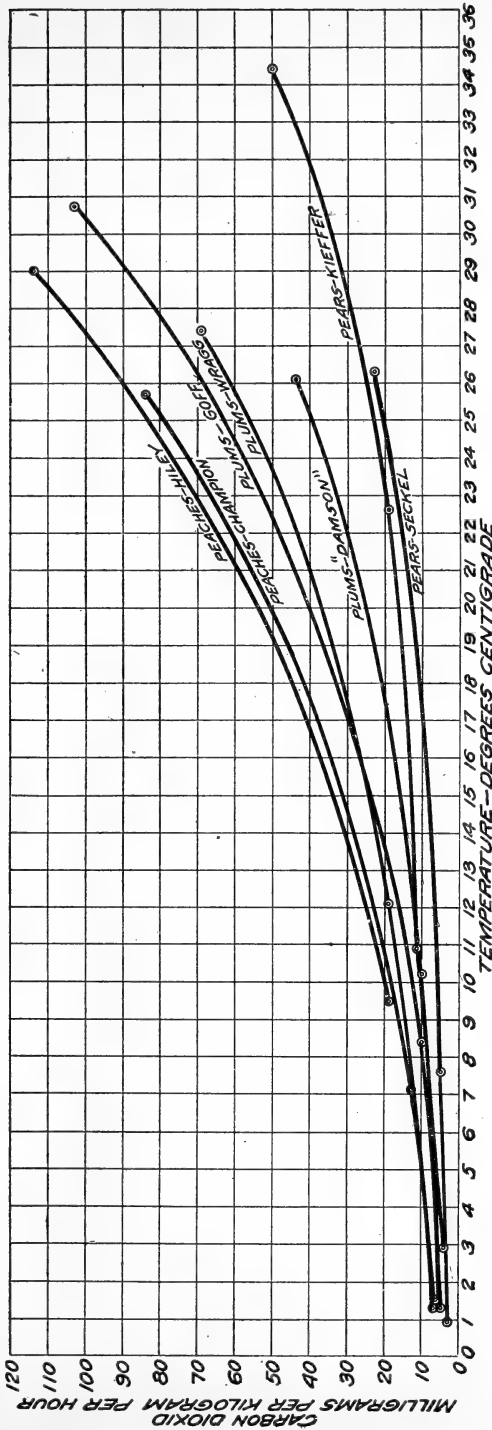
FIG. 6.—Effect of temperature on the rate of respiration of peaches, pears, and plums.
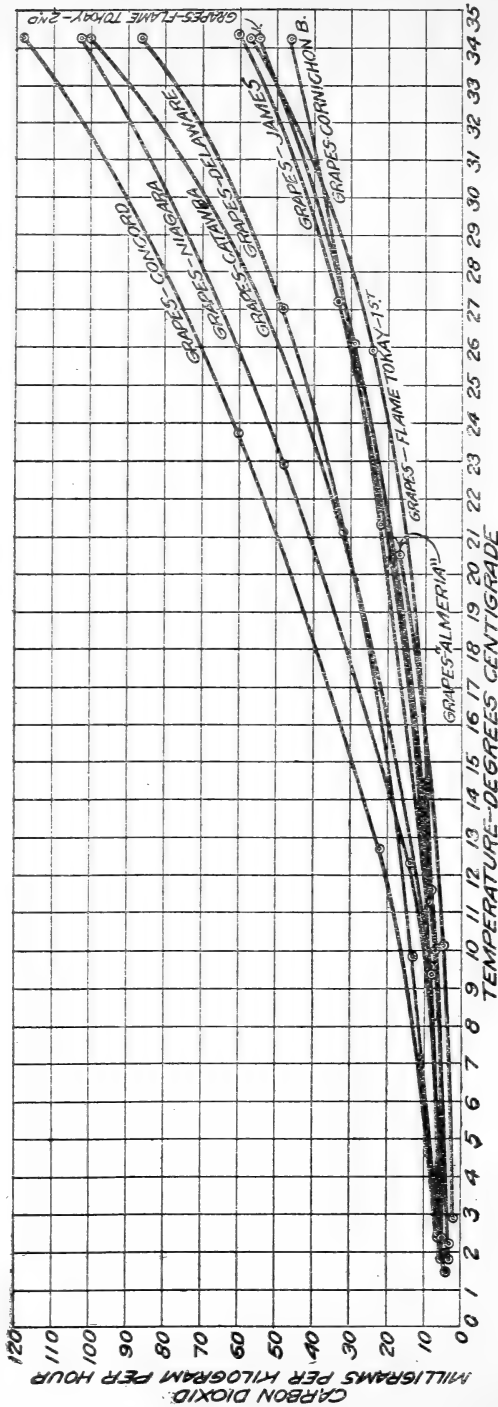
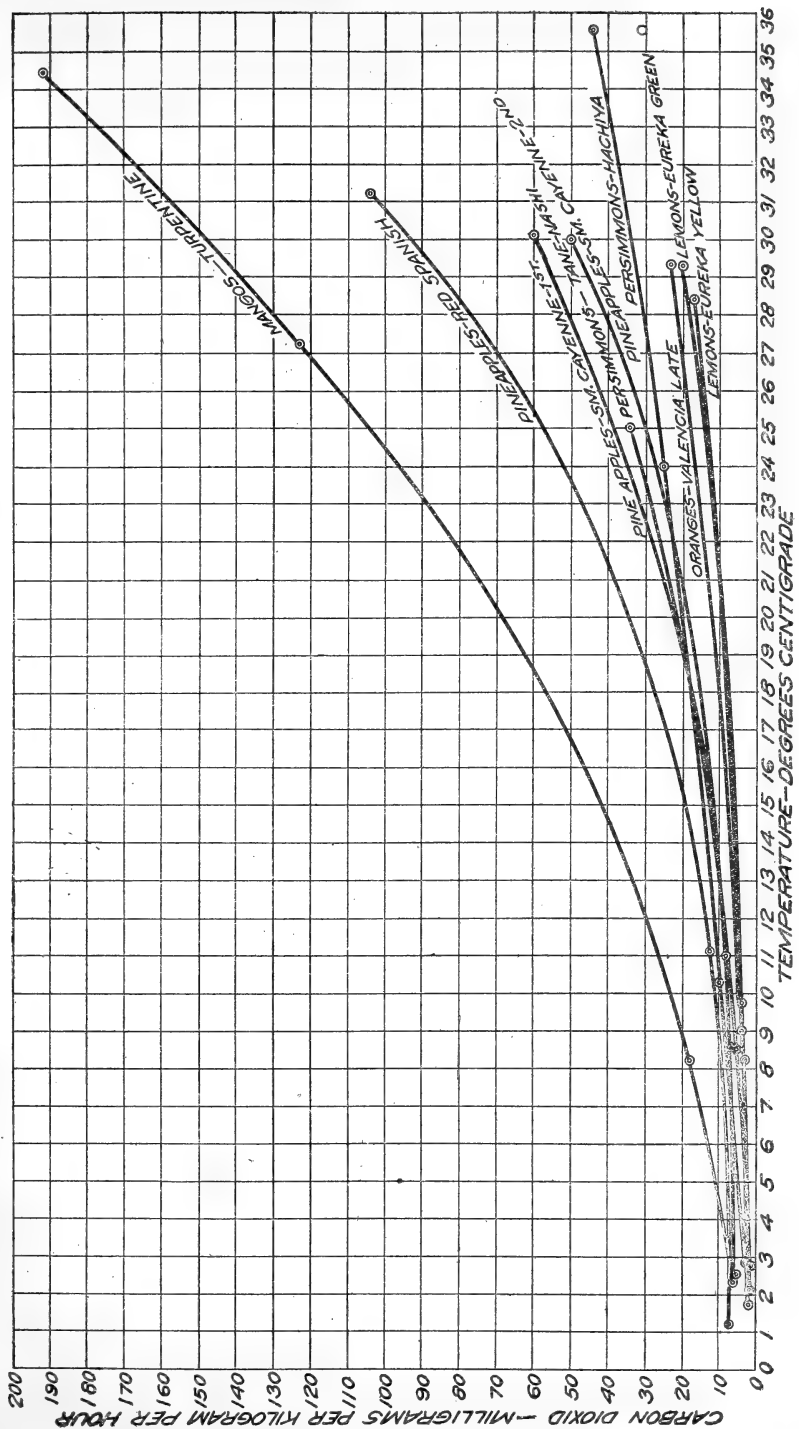Fig. 7.—Effect of temperature on the rate of respiration of grapes.

Fig. 8.—Effect of temperature on the rate of respiration of lemons, oranges, persimmons, mangos, and pineapples.

As was foreseen from the study of the literature, a rise in temperature was accompanied by a very rapid increase of respiratory activity, and, as the data accumulated, the general resemblance of the curves to each other became increasingly evident. There seemed to be some general law regulating the increase of respiration with temperature. At this point, material assistance was received from C. S. Hudson, of this bureau. The curve under consideration at the time was that of Delaware grapes. The values at the four different temperatures are given in Table 1 and graphically represented in fig. 9. At Mr. Hudson's suggestion, besides plotting the actual values found for the carbon dioxid per hour per kilogram of fruit, the logarithm of the carbon dioxid figure was used, and the points were found to lie nearly in a straight line. The equation of this line by construction is—

$$\log (CO_2)_t = \log (CO_2)_{t=0^\circ} + at$$

or if $(CO_2)_t = y$ and $(CO_2)_{t=0^\circ} = y_0$, then

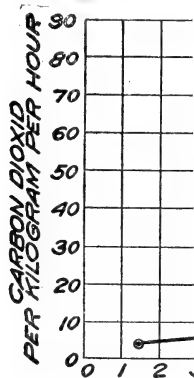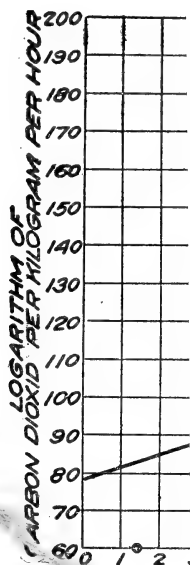$$\log y = \log y_0 + at. \qquad \text{(Equation 1.)}$$

Logarithm y_0 and a[1] may be readily determined by inspection;[2] log y_0 (the intercept on the y axis) equals 0.78, and $30a$ equals $1.790 - \log y_0$, equivalent to 1.010, therefore a equals 0.0337.

The location of the straight line most nearly representing the facts is more or less empirical and a number of circumstances must be considered. A small error in the determination of the activity at low temperatures affects the results when plotted as the logarithm much more than the same numerical error at higher temperatures. Hence less weight should be given to the cold-storage values than to the others. With many fruits the activity has been found to decline when held at high temperatures. For this reason less consideration should be given to the data obtained at incubator temperature than to those obtained from fruit kept at refrigerator and at room temperatures. While certain inaccuracies are thus unavoidable, this method of expressing the results has been found of great value in comparing the different fruits with one another. The results obtained by plotting the data in this way are given graphically in figs. 10 to 14, inclusive.

From equation 1, written in the exponential form $y = y_0 10^{at}$, it is possible to calculate the number of times that y will be increased for any given rise in temperature. If the activity is y' at temperature t', at t'' the activity $y'' = y' 10^{a(t''-t')}$. If $t'' - t' = 10^\circ$ C., $y'' = y' 10^{10a}$. The number whose logarithm is $10a$ is the number of times by which the activity is increased for 10° C.

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[1] The constant a is defined on p. 24.   [2] See fig. 9.

Chart 1 (top):
Y-axis: LOGARITHM OF CARBON DIOXID PER KILOGRAM PER HOUR (60–200)
X-axis: TEMPERATURE—DEGREES CENTIGRADE (0–35)
Label: GRAPES—DELAWARE

TEMPERATURE	CARBON DIOXID PER KILOGRAM PER HOUR	LOGARITHM OF CARBON DIOXID PER KILO PER HOUR
34.2	86	1.9345
27.0	48	1.6812
9.8	13	1.1139
1.4	4	.6021

LOG Y = LOG Y₀ + AT

$$\log Y = \log Y_0 + AT$$

Chart 2 (bottom):
Y-axis: CARBON DIOXID PER KILOGRAM PER HOUR (0–90)
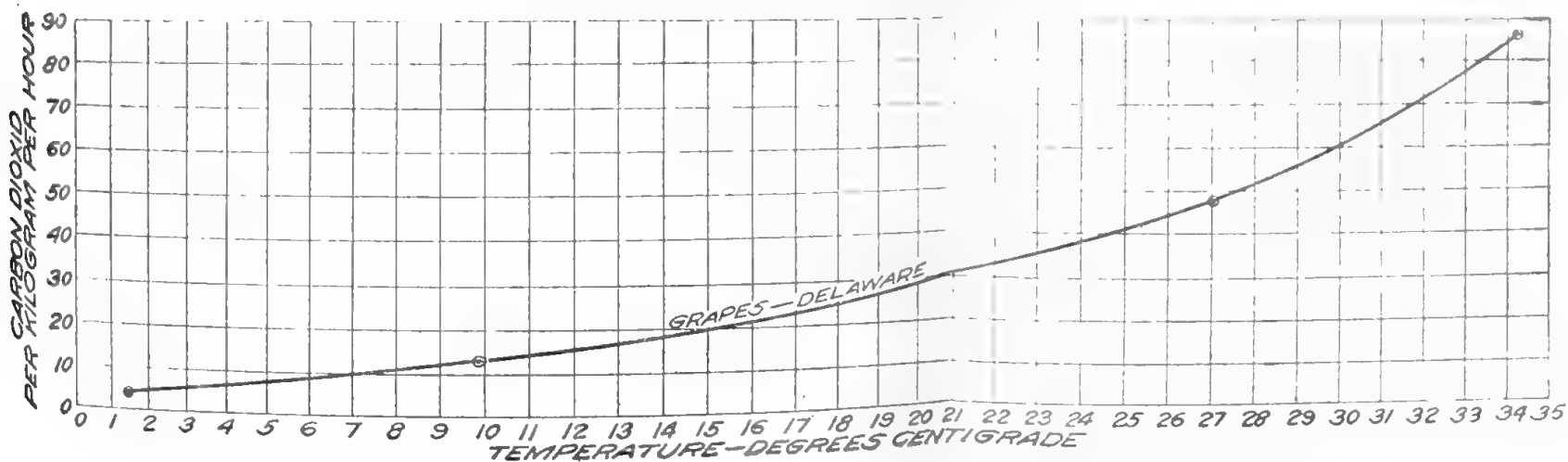X-axis: TEMPERATURE—DEGREES CENTIGRADE (0–35)
Label: GRAPES—DELAWARE
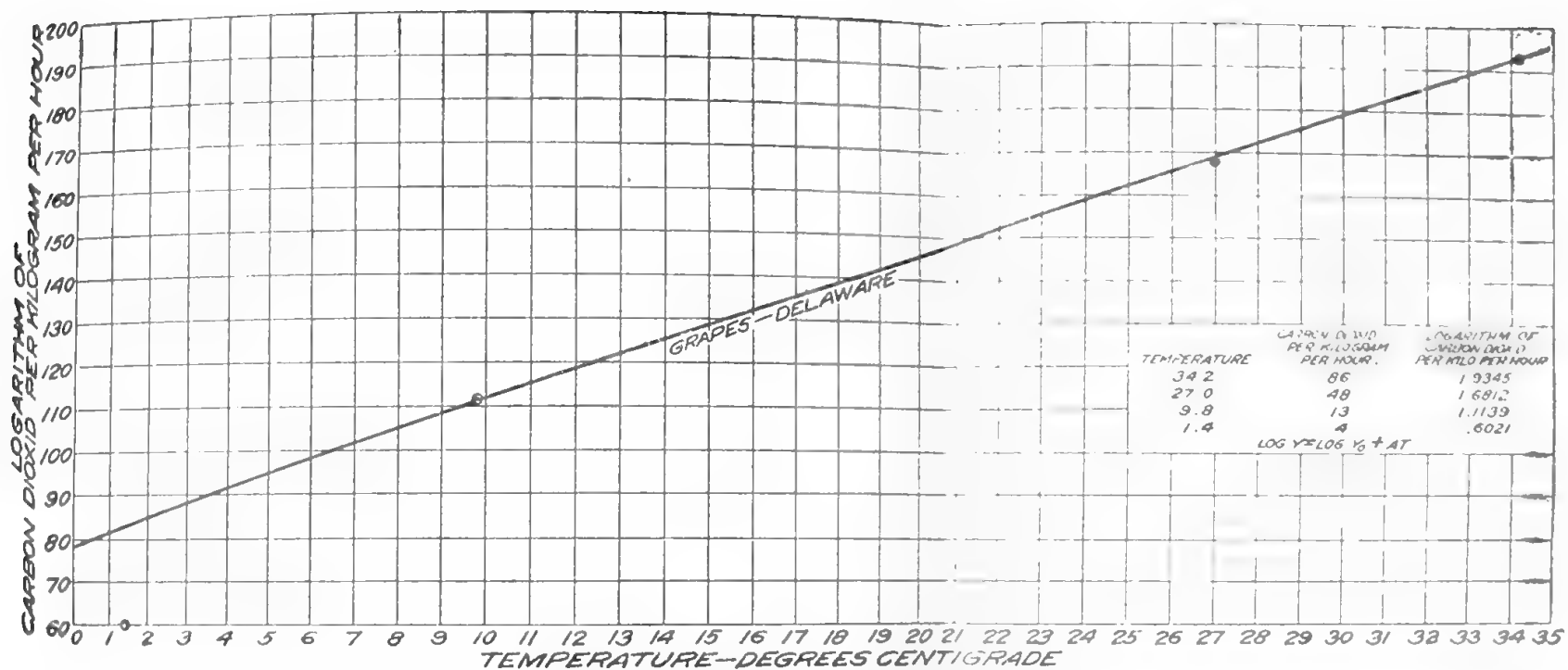
FIG. 9.—Data on the respiration of Delaware grapes, showing the evolved carbon dioxid plotted directly and logarithmically

95678°—Bull. 142—11.   (To face page 20.)   No. 1.
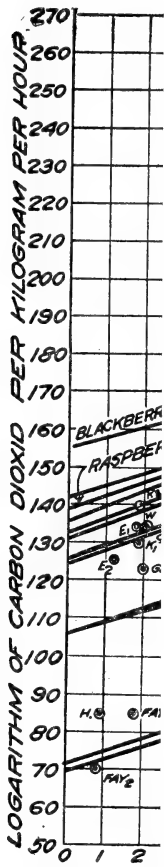
FIG. 10.—Effec

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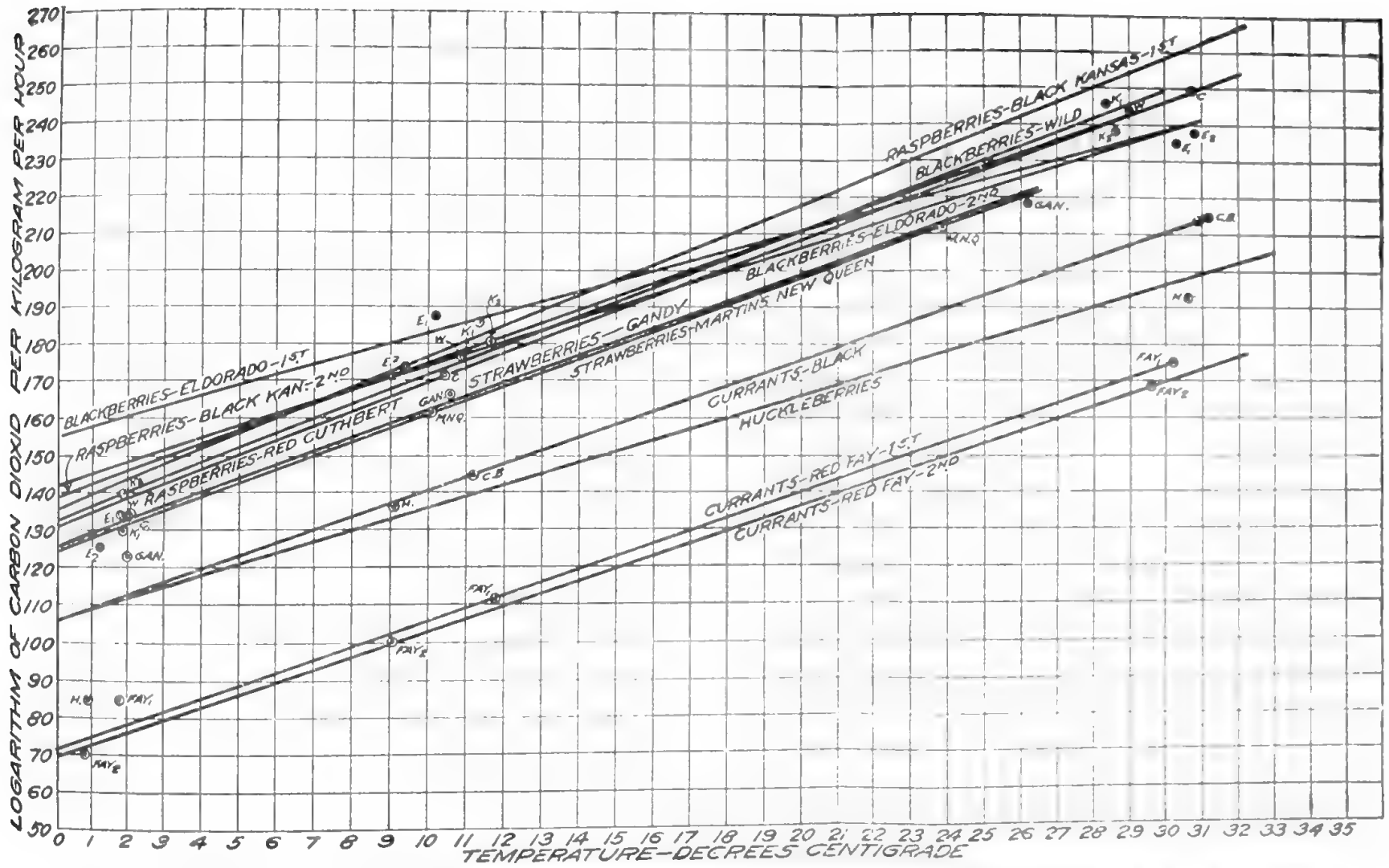
Fig. 10.—Effect of temperature on the rate of respiration of blackberries, currants, huckleberries, raspberries, and strawberries, plotting the carbon dioxid logarithmically.

Fig. 11.—Effect of temperature on the rate of respiration of peaches and apples, plotting the carbon dioxid logarithmically.
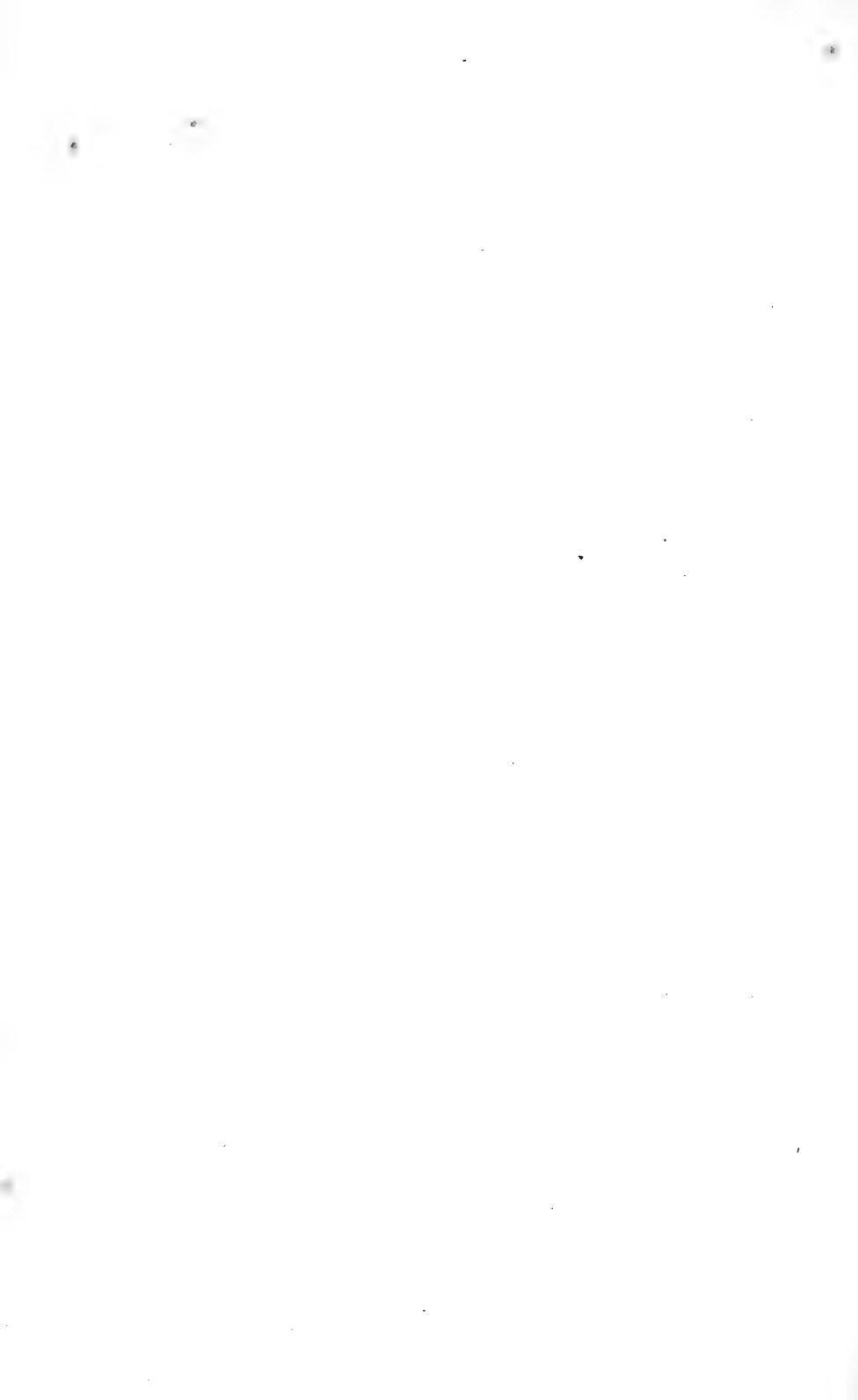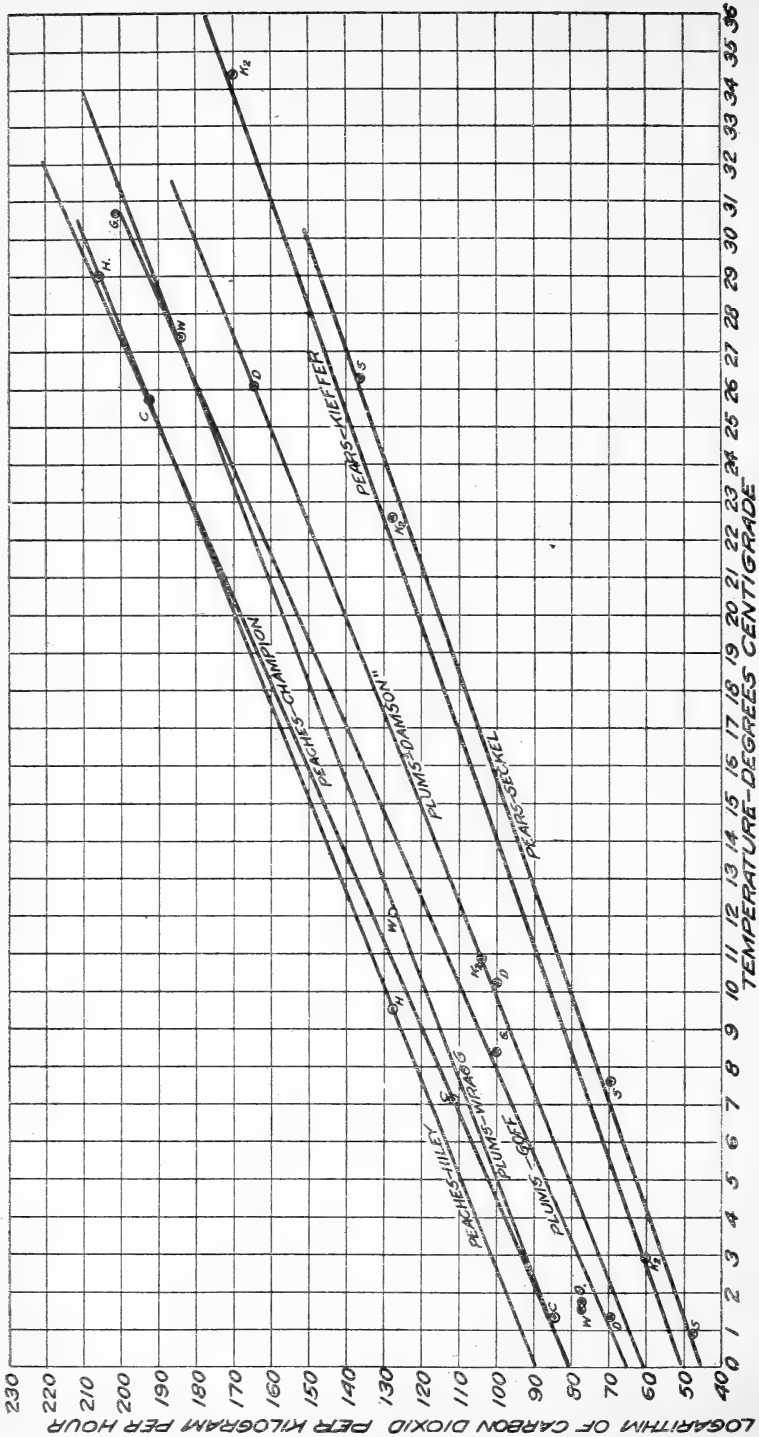
FIG. 12.—Effect of temperature on the rate of respiration of peaches, pears, and plums, plotting the carbon dioxid logarithmically.
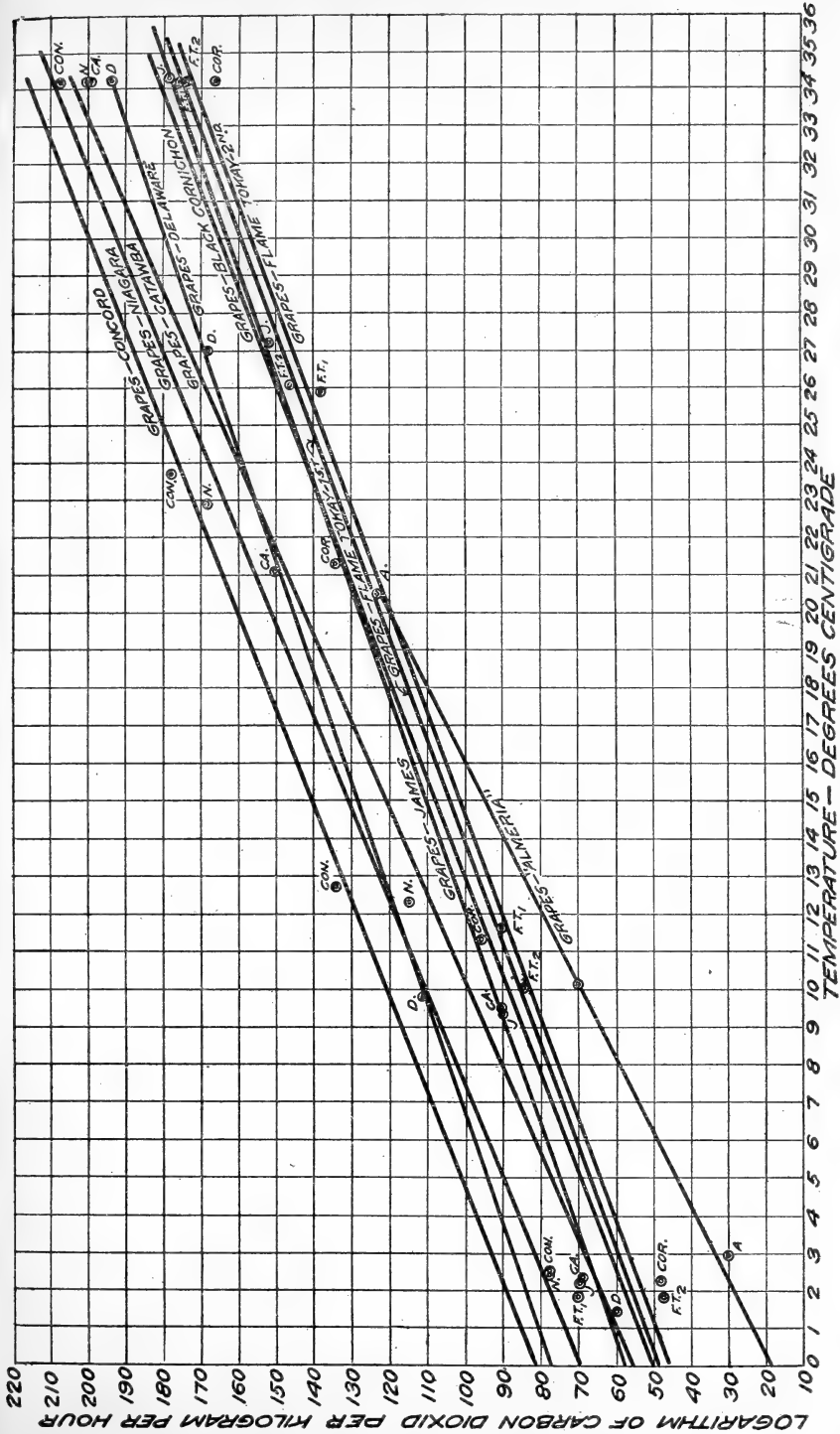
FIG. 13.—Effect of temperature on the rate of respiration of grapes, plotting the carbon dioxid logarithmically.

It is also possible to calculate the range of temperature through which it will be necessary to warm the fruit before the activity is doubled or changed by any other factor.   If the activity is doubled—

$$y'' = y' 10^{a(t'' - t')}$$

and

$$\frac{y''}{y'} = 10^{a(t'' - t')} = 2.$$

$$t'' - t' = \frac{\log 2}{a}.$$

In Table 2 are given the constants derived by inspection from the straight lines drawn among the points determined by plotting the logarithms of the carbon dioxid formed per kilogram per hour. Logarithm y_o is the constant for any special fruit, and the number corresponding (y_o) is the calculated respiratory activity at 0° C. expressed as milligrams of carbon dioxid per kilogram per hour.   The constant a is a more general constant, changing slightly from one series of determinations to another, and is the rate at which the logarithm of the respiratory activity changes per degree of rise in temperature. It corresponds to the constant K of unimolecular chemical reactions in which the independent variable is time.   The number of times by which the respiratory activity increases for 10° C. is also given, as well as the temperature intervals through which the fruits must be warmed in order that the activity be doubled.

TABLE 2.—*Constants determined by inspection from figs. 10–14, the increment for* **10° C.,** *and the temperature increase required to double the activity.*

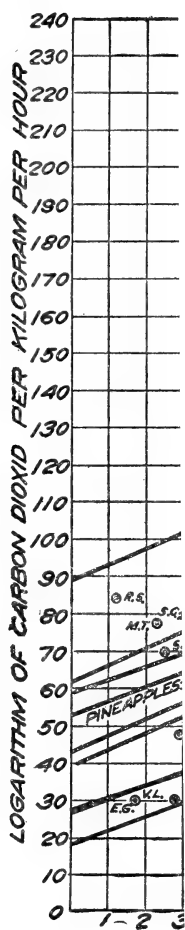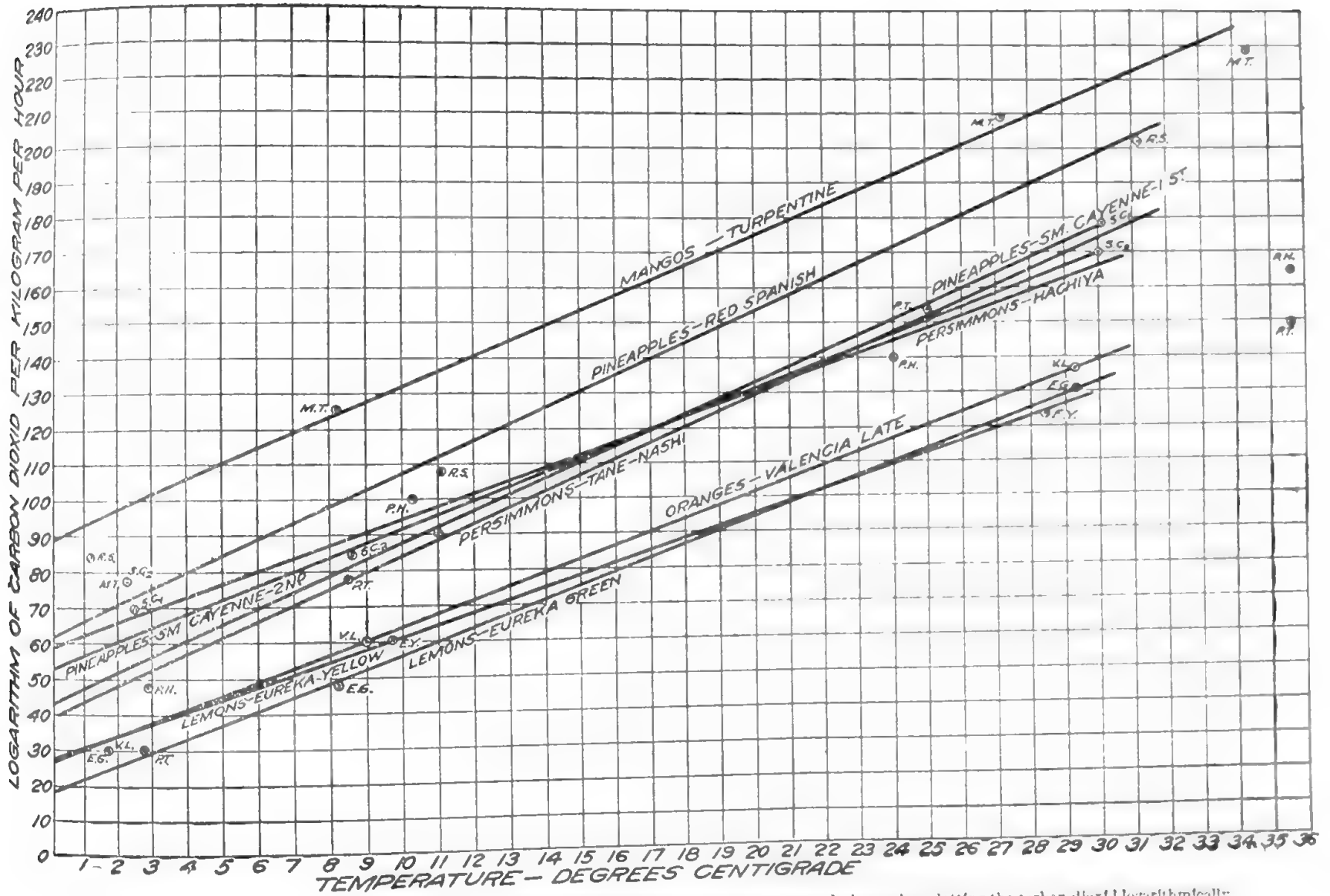| Kind and variety of fruit.	Log y_o.	y_o.	a.	Increment for 10° C.	Temperature increase required to double the activity.
Strawberries:					
Martin's New Queen	1.240	17.4	0.0366	2.32	8.2
Gandy	1.250	17.8	.0365	2.32	8.2
Black raspberries:					
Kansas	1.357	22.8	.0408	2.56	7.4
Do	1.390	24.6	.0357	2.28	8.4
Red raspberries:					
Cuthbert	1.310	20.4	.0384	2.42	7.8
Blackberries:					
Eldorado	1.550	35.5	.0277	1.89	10.9
Do	1.420	26.3	.0320	2.09	9.4
Wild	1.320	20.9	.0390	2.45	7.7
Red currants:					
Fay	.710	5.1	.0344	2.21	8.8
Do	.690	4.9	.0336	2.17	9.0
Black currants	1.060	12.0	.0347	2.22	8.7
Do	1.080	11.5	.0341	2.19	8.8
Huckleberries:					
Gaylusaccia baccata	1.055	11.4	.0302	2.00	10.0
Peaches:					
Carman (hard-green)	.818	6.6	.0461	2.88	6.5
Carman (ripened)	1.070	11.8	.0374	2.37	8.1
Do	1.000	10.0	.0377	2.38	8.0
Hiley	.895	7.9	.0402	2.52	7.5
Champion	.800	6.3	.0440	2.75	6.8
Connett	1.010	10.2	.0357	2.28	8.4
Do	.930	8.5	.0359	2.29	8.4
Elberta	.920	8.3	.0357	2.28	8.4
Plums:					
Wragg	.810	6.5	.0381	2.40	7.9
Goff	.655	4.5	.0438	2.74	6.9
"Damson"	.610	4.1	.0397	2.49	7.6

FIG. 14.—E

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FIG. 14.—Effect of temperature on the rate of respiration of lemons, oranges, persimmons, mangos, and pineapples, plotting the carbon dioxid logarithmically.

TABLE 2.—*Constants determined by inspection from figs. 10–14, the increment for 10° C., and the temperature increase required to double the activity*—Continued.

Kind and variety of fruit.	Log y_o.	y_{o_1}	a.	Increment for 10° C.	Temperature increase required to double the activity.
Pears:					
Seckel	.455	2.9	.0348	2.23	8.7
Kieffer	.510	3.2	.0350	2.24	8.6
Apples:					
Jefferis	.798	6.3	.0314	2.06	9.6
Summer Pearmain	.825	6.7	.0322	2.10	9.4
Yellow Bellflower	.770	5.9	.0310	2.04	9.7
Red Pearmain	.630	4.3	.0333	2.15	9.0
Missouri Pippin	.660	4.6	.0380	2.40	7.9
Grapes:					
James	.580	3.8	.0349	2.24	8.6
Delaware	.780	6.0	.0337	2.17	8.9
Concord	.810	6.5	.0393	2.47	7.7
Niagara	.695	5.0	.0408	2.56	7.4
Catawba	.550	3.5	.0437	2.74	6.9
Flame Tokay	.460	2.9	.0367	2.33	8.2
Do	.485	3.1	.0368	2.33	8.2
Black Cornichon	.500	3.2	.0383	2.41	7.9
"Almeria"	.185	1.5	.0505	3.20	6.0
Oranges:					
Valencia (late)	.265	1.8	.0375	2.37	8.0
Lemons:					
Eureka (green)	.180	1.5	.0381	2.40	7.9
Eureka (yellow)	.270	1.9	.0341	2.19	8.8
Pineapples:					
Red Spanish	.620	1.5	.0455	2.85	6.6
Smooth Cayenne	.430	2.7	.0448	2.81	6.7
Do	.530	3.4	.0389	2.45	7.7
Mangos:					
Turpentine	.886	7.7	.0430	2.69	7.0
Japanese persimmons:					
Tane-nashi	.390	2.5	.0450	2.82	6.7
Hachiya	.585	3.8	.0358	2.28	8.4
Average			.0376	2.376	8.01

DISCUSSION OF RESULTS.

Strawberries, variety Martin's New Queen, were first experimented with, using temperatures of 23.9° and 10.1° C.; 130 and 41 mg per kilogram per hour of carbon dioxid were formed, respectively. Upon inspection of the results of this experiment, Mr. Taylor suggested that a third temperature, that of commercial cold storage, be added to the other temperatures at which it was proposed to determine respiratory activities. Accordingly, in the subsequent experiments a cold-storage temperature was used when possible, thus considerably extending the scope of the work. The study of the respiratory activities of the Gandy variety gave values similar to those found in case of Martin's New Queen, and the curves expressing the results are practically parallel.

Black raspberries, variety Kansas, were found to be intensely active. At 28.4° C. the first lot formed 284 mg of carbon dioxid per kilogram per hour.

Blackberries, both wild and cultivated, and red raspberries were also found to be intensely active, the latter forming 311 mg of carbon dioxid per kilogram per hour at 30.8° C.

Red currants were relatively inactive when compared with the other small fruits. At temperatures of 30.2°, 11.8°, and 1.8° C., 56, 13, and

7 mg of carbon dioxid per kilogram per hour, respectively, were formed. The results of the second day's run were practically a duplicate of those of the first day.

Black currants and huckleberries were intermediate in physiological activity between raspberries, blackberries, and strawberries on the one hand and red currants on the other.

Carman peaches when hard-green respired slightly less rapidly than when ripe. After ripening, however, the respiratory activity decreased slightly but decisively. With Hiley peaches results were obtained at but two temperatures, as the determination at the cold-storage temperature was lost. The curve of Champion peaches closely paralleled that of the Hiley and of the fully ripened Carman. In the case of Connett peaches there was a distinct decline in physiological activity from one day to another. During the first day at 29.0°, 10.7°, and 1.1° C., 104, 25, and 7 mg of carbon dioxid per kilogram per hour were formed, respectively; while during the second day's run, at temperatures of 29.6°, 11.0°, and 1.1° C., 93, 22, and 6 mg, respectively, were collected. The curve of Elberta peaches closely paralleled that of Connett peaches during the second day's run and seemed distinctly less active physiologically than the other sorts.

A special lot of Dover peaches picked on August 24, at three different stages of ripeness, from the same tree at the Arlington farm, was separated by A. V. Stubenrauch, of the Bureau of Plant Industry, into three lots according to ripeness—hard-green, hard-ripe, and tree or eating-ripe. The measurement of the rate of respiration was begun on the same day. The peaches respired at the rate of 101, 98, and 101 mg, respectively, showing that no marked changes in rate of respiration occur during ripening on the tree. The data are as follows:

TABLE 3.—*Respiration data on peaches picked at three stages of ripeness.*

Stage of ripeness.	Number.	Weight.	Interval.	Temperature.	Carbon dioxid (milligrams per kilogram per hour).
		Grams.	*Hours.*	° *°C.*	
Hard-green	14	1,570	17.8	28	101
Hard-ripe	15	1,703	18.0	28	98
Tree-ripe	13	1,458	18.3	28	101

Plums, apples, and pears were less active than peaches. Summer apples respired with perceptibly greater rapidity than the winter varieties.

The Concord, Delaware, Niagara, and Catawba grapes were found to be distinctly more active than the Vinifera grapes, Flame Tokay, Black Cornichon, and "Almeria," or the Rotundifolia variety James.

Mangos were nearly as active as peaches. The citrus fruits were exceedingly inactive.

No satisfactory theory based on the composition or size of fruits has been found to account for the differences in the respiratory activity. A few moments' inspection shows that the rate of respiration is not a direct function of content of sugar or of acid, and does not depend upon size, as Japanese persimmons are richer in sugar than strawberries, yet are less active; oranges and lemons, which differ greatly in acid content, have about the same respiratory activity; red currants differ greatly in respiratory activity from black currants, although they are nearly the same in size. Generally speaking, the fruits which have a short growing period, mature rapidly, and become over-ripe quickly—as strawberries, raspberries, and blackberries—are very active physiologically. At the other extreme are the slowly developing citrus fruits, which are very inactive. Intermediate in these respects are the other fruits. Peaches have a shorter life history than apples and are more active. Summer apples do not keep so well as winter apples, and respire more rapidly.

In the case of 29 series of determinations the values at the cold-storage temperatures fall below the empirically drawn lines, and it is therefore probable that in cold storage most fruits respire less actively than would be calculated from equation 1, page 20. In 11 out of 15 determinations the value at the incubator temperatures falls below the line, and it is probable that where this occurred the rate of respiration declined during the period of observation. In general, however, the respective respiratory activities are well defined by equation 1, in which log y_0, determined experimentally as described on page 20, is the constant characteristic for each kind of fruit and in which the constant a is nearly constant for all fruits, varying slightly from one fruit to another.

In calculating the standard deviation and the probable error of the constant a from the mean value 0.0376, formulæ given by Davenport and Rietz [1] have been used. The standard deviation equals

$$\sqrt{\frac{\Sigma D^2}{N}} = 0.00457,$$

where ΣD^2 is the sum of the squares of the differences from the arithmetical mean, and N is the number of observations. The probable error,

$$\pm E = \pm \frac{\text{Standard Deviation}}{\sqrt{N}} \times 0.6745 = \pm 0.00044,$$

"determines the degree of confidence we may have in using the mean as the best representative value of a series of observations." [2]

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[1] Univ. of Illinois, Agri. Exp. Sta. Bul. 119, 1907.

[2] Mellor, Higher Mathematics for Students of Chemistry and Physics, 1905, p. 514.

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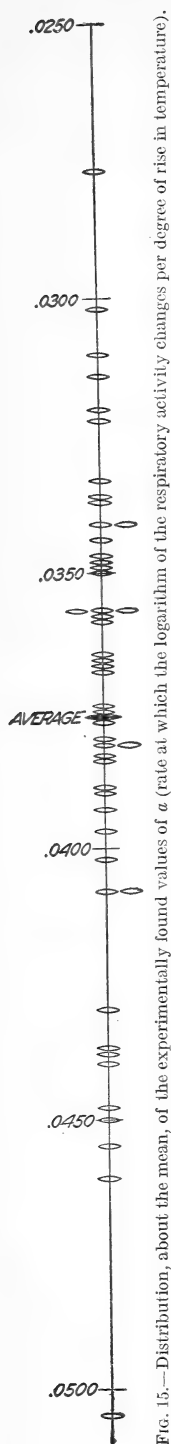AVERAGE

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Fig. 15.—Distribution, about the mean, of the experimentally found values of a (rate at which the logarithm of the respiratory activity changes per degree of rise in temperature).

The chances are even that the best value of $a = 0.0376 \pm E$, and are 4.5 to 1 that it is $0.0376 \pm 2E$, and 21 to 1 that it is $0.0376 \pm 3E$, etc.[1] The distribution of the forty-nine determined values of a with respect to the mean value 0.0376 is shown graphically in figure 15.

By grouping arbitrarily into classes a frequency curve may be constructed in the usual way. The form of the curve changes greatly, however, according as the classes are chosen and, as no relation not already well illustrated by figure 15 is shown, the frequency curve is not given. It will be seen that a large proportion of the determinations of a are very near the mean, while the few high and low values are far removed.

The results obtained by Clausen [2] in the study of the respiration of wheat, lupin seedlings, and syringa (lilac) between the temperatures 0° and 25° C. have been cited by van't Hoff [3] as an illustration of the fact that the rate of increase in intensity of respiration with temperature is similar to the rate of increase of chemical reactions. A rise in temperature of 10° increased the respiration intensity "2.46 times (on the average) with wheat, 2.45 times with lupins, and 2.47 times with syringa (lilac)." Similar facts have been developed by Blackman [4] in discussing the data obtained by Miss Matthaei [5] in the study of the effect of temperature on the intensity of respiration and assimilation. Here the number of times by which the intensity increased for 10° C. rise has been calculated to be 2.4 and 3.1, respectively. In the determinations of the rate of respiration of fruits presented in this report the average coefficient for a rise in temperature of 10° C. is 2.377 ± 0.024.[6] That the respiratory processes of fruits follow the same rule as do the chemical reactions is a fact of great significance, indicating that the fundamental life processes of fruits are chemical.

[1] Davenport and Rietz, loc. cit.

[2] Landw. Jahrbücher, 1890, 19: 893.

[3] Studies in Chemical Dynamics, trans. by Ewan, 1896, p. 126.

[4] Annals of Botany, 1905, 19: 281. See also Nature, 1908, 78: 556.

[5] Royal Society, London, Philos. Trans. 1905 (B). 197 : 65.

[6] Calculated as shown on page 20. The quantity ± 0.024 is the deviation due to the probable error of a.

II. EFFECT OF PICKING ON THE RATE OF EVOLUTION OF CARBON DIOXID BY PEACHES.

In the discussion of the rate of the formation of carbon dioxid by fruits Mr. Taylor suggested that experiments be made on peaches in the orchard to determine whether or not they received a stimulus on picking which would be made known by an increase in the rate of evolution of carbon dioxid; by measuring the rate of change an idea of the magnitude of the stimulus to the life processes might be obtained. Field studies were accordingly made and facilities were provided at the Arlington Experiment Farm, where valuable cooperation was given in the conduct of the investigation. So far as known no data are on record of similar studies.

APPARATUS AND METHOD EMPLOYED.

Pure air was run through a jar containing peaches attached to the trees and the amount of carbon dioxid given off during a known period contrasted with that formed by peaches at the same stage of ripeness after picking.

The jar which contained the attached fruit was provided with a split cover which could be fastened together air-tight by means of long screws after it had been taken apart to admit the branch. The joint between the branch and the cover and the joint of the cover were made air-tight either by use of grafting wax or a specially prepared rubber compound used by electricians. The large percolating jars used in experiments 1 and 2 were fitted with brass collars provided with threaded bolts and thumbscrews by which the covers of paraffined hard maple were brought tightly against a rubber gasket at the edge of the jar.[1]

The jars were screened from direct sunlight to avoid the rapid rise in temperature due to the "greenhouse" effect; and in order to keep both lots at the same temperature because of its marked effect on the rate of respiration, they were kept near each other under the tree at about the same height.

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[1] L. J. Briggs, Bureau of Plant Industry, assisted in designing these covers and having them made.

The air entering each jar was purified by passing it through a glass tube, 35 cm long and 5 cm in diameter, filled with soda lime. It was then drawn through a bottle containing baryta water and into the jar. The tube entering the container terminated near its cover, while the exit tube reached nearly to the bottom. The air drawn from the jars passed through a Reiset absorption apparatus, then through a wash bottle containing baryta water and to a suction pump. A failure of the soda lime to remove carbon dioxid from the entering air would, of course, be shown by the appearance of turbidity in the first bottle of baryta water, while the last bottle of baryta water would reveal a failure of the Reiset tube to absorb the carbon dioxid completely. In three experiments, the results of which are detailed on page 32, these bottles indicated that the air was properly purified and that there was a complete absorption in the Reiset tubes of the carbon dioxid formed by the fruit.

The air was aspirated through each apparatus at the rate of about 2 liters per hour and was conveyed in glass or copper tubes, avoiding use of rubber tubing as far as practicable on account of the recognized selective absorption of carbon dioxid by rubber and because of the marked tendency of much of the rubber tubing on the market to develop minute cracks when exposed to the weather.

The carbon dioxid was estimated by the method employed in the study of the effect of temperature on fruit respiration. (See page 11.)

As a good many difficulties were encountered during the progress of the work, only three experiments were completed. It was hard to make the joint air-tight between the branch and the jar, and the percolating jars cracked at very inopportune times on account of the warping of the covers. One of the jars cracked during experiment 1. In experiment 2, as no other percolating jar was available, a tubulated desiccator was substituted, in which the picked fruit was held. In experiment 3 a large museum jar with a cover made of hard rubber was substituted for the percolating jar for fruit attached to the tree. It was planned to support both jars under the tree on tripods, but these proved not to be sufficiently stable, and the jars were therefore attached by means of universal clamps to half-inch vertical iron rods, the sharpened ends of which were driven firmly into the ground. Only sound normal fruits from the same portion of the same tree were selected. The foliage was carefully trimmed away from the group of fruits selected for inclosure in the jar while attached to the tree. The detached fruit was weighed at the beginning of each experiment and the attached fruit at its conclusion.

RESULTS OBTAINED.

The data of the three experiments are shown in the accompanying table (p. 32).

Experiment 1 on Mountain Rose peaches was started in the afternoon of August 10 and finished during the forenoon of the following day, an interval of $18\frac{2}{3}$ hours. Five peaches weighing 325 grams attached to the tree gave off 0.572 gram of carbon dioxid at the rate of 94 mg per kilogram per hour. Five peaches weighing 297 grams detached from the tree gave off 0.497 gram of carbon dioxid during the same period at the rate of 89.5 mg per kilogram per hour. As before mentioned, the jar containing the fruit attached to the tree cracked during the experiment, and slight contamination due to carbon dioxid from the outside air probably occurred, accounting for the higher values obtained. The results of the experiment are, therefore, somewhat inexact, but indicate that there is no marked acceleration in evolution of carbon dioxid due to picking.

The results of experiment 2 showed that five Mountain Rose peaches attached to the tree and weighing 312 grams gave off 0.462 gram of carbon dioxid during 18 hours, the rate being 82.2 mg per kilogram per hour, and that five picked Mountain Rose peaches weighing 347 grams gave off 0.466 gram of carbon dioxid during the same interval at the rate of 74.7 mg per kilogram per hour. At the conclusion of the experiment a very slight leak was found in the apparatus connected with the fruit attached to the tree. This possibly accounts for the higher results obtained. Again, as in experiment 1, the results indicated that there is little or no acceleration in carbon dioxid due to picking.

Experiments 1 and 2 were started near the end of the afternoon of one day and finished during the forenoon of the next, because it was desired to avoid possible disturbances due to temperature differences which might occur even though the jars were shaded, as it was possible that reflected light and heat might have influenced the temperatures unequally. During experiment 3, however, a period of cool, cloudy weather made it possible to continue the experiment during three days. There was no sunshine during the first two days, but during the late forenoon of the third day the sun shone for several hours.

In experiment 3 carbon dioxid was formed by six hard-ripe Champion peaches attached to the tree, at the rate of 51.7, 55.5, and 79 mg per kilogram per hour, during the three days, respectively. Picked fruit gave off carbon dioxid at the rate of 54.4, 56.9, and 82 mg per kilogram per hour during the same intervals. Again, as in

experiments 1 and 2, no acceleration in rate of respiration is shown. At the conclusion of the experiment a very slight leak was detectable in each of the systems, but it was probably not sufficiently large to affect the results.

The results, therefore, show that if any change in the rate of respiration of peaches is caused by picking, such change is very small and not measurable by the method employed.

TABLE 4.—*Data obtained in the study on the effect of picking on the rate of evolution of carbon dioxid.*

Experiment number.	Variety and description.	Date.	Time of experiment.			Number of peaches.	Weight.	Normal hydrochloric acid required.	Carbon dioxid.	Carbon dioxid (grams per kilogram).	Carbon dioxid (milli-grams per kilogram per hour).
			Beginning.	End.	Interval.						
		1910.	*p. m.*	*a. m.*	*Hours.*		*Gms.*	*cc.*	*Grams.*		
1	Mountain Rose (hard-ripe):	*August.*									
	Attached to tree...........	10–11	3.40	10.20	18.67	5	325	13.0	0.572	1.760	[1] 94.0
	Detached.................	10–11	3.40	10.20	18.67	5	297	11.3	.497	1.673	89.5
2	Mountain Rose (hard-ripe):										
	Attached to tree...........	12–13	5.00	11.00	18.0	5	312	10.5	.462	1.480	[2] 82.2
	Detached.................	12–13	5.00	11.00	18.0	5	347	10.6	.466	1.344	74.7
3	Champion (hard-ripe):			*p. m.*							
	Attached to tree...........	16–17	3.10	3.10	24.0	6	539	15.2	.667	1.241	[3] 51.7
	Detached.................	16–17	3.10	3.10	24.0	7	627	18.6	.818	1.305	[3] 54.4
3	Champion (hard-ripe):										
	Attached to tree...........	17–18	3.10	2.00	22.83	6	539	15.5	.682	1.265	[3] 55.5
	Detached.................	17–18	3.10	2.00	22.83	7	627	18.5	.814	1.298	[3] 56.9
3	Champion (hard-ripe):										
	Attached to tree...........	18–19	2.00	1.30	23.5	6	539	22.8	1.0032	1.861	[3] 79.0
	Detached.................	18–19	2.00	1.30	23.5	7	627	27.5	1.2100	1.930	[3] 82.0

[1] The jar cracked during the run.   Higher result possibly due to contamination by outside air.
[2] A very slight leak perceptible.
[3] A barely detectable leak found in both systems.

III. RATE OF ACCUMULATION OF HEAT IN THE RESPIRATION OF FRUIT UNDER ADIABATIC CONDITIONS.

CAUSES OF SELF-HEATING.

As stated in Part I (p. 7), two attempts to determine the effect of temperature on the respiration of bananas failed because of the very rapid increase in respiration which occurred, incident to the processes of ripening, during the periods of observation at room temperature. It was observed that the walls of the desiccators in which the fruit was kept became wet on the inside. In attempting to discover the cause of this, the bananas were found to be from 1.4° to 1.9° C. warmer than the desiccators. Attention was thus drawn to the phenomenon of self-heating exhibited by certain agricultural products, many similar instances being readily found. The heating of bananas has long been known to the shippers. Carrots, sugar beets, corn and other grains, cotton seed, hayseed, hay, manure, tobacco, and stover all heat readily, especially if stored when moist and under such conditions that the heat as produced is not dissipated.

An inspection of the literature shows that self-heating may be due to several causes. Heating caused by physiological processes probably operates first and raises the temperature to the point at which other causes, enzymotic or chemical, come into play. Oxidizing enzyms are the active agents in many cases. They are, for example, probably the dominating factor in the fermentation of tobacco,[1] working most actively at the high temperatures which may have occurred as a result of respiration. The microorganisms also induce oxidation or other chemical changes involving the liberation of heat. Finally there is the chemical oxidation which often supervenes when one or more of the other causes has raised the temperature to the point at which chemical action is appreciable. The final result may then be charring, or even combustion. The difficulties in deciding which of the several causes last named are operative in spontaneous heating are interestingly discussed by Rahn.[2]

The operation of the physiological processes in respiration seems to be the general cause of self-heating. As the law expressing the increase of the rate of respiration with temperature is now approximately known, it has seemed worth while to calculate the rate at which the temperature would increase when adiabatic conditions are assumed—that is, conditions under which there is no gain or loss in heat from the outside. The results of such a calculation should be of value in the study of self-heating.

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[1] U. S. Dept. Agr., Report No. 59, Loew, Curing and Fermentation of Cigar-leaf Tobacco.
[2] Michigan Agricultural College Experiment Station, Technical Bul. 5, 1910.

FORMULA FOR CALCULATING RATE OF HEAT ACCUMULATION.

To determine the amount of heat generated in respiration, it is necessary to know the thermal equivalent of the carbon dioxid formed, which has been assumed to result from the combustion of sucrose, which produces 3.96 calories per gram, when burned completely, in the respiration calorimeter.[1] As the reaction expressing the combustion is

$$C_{12}H_{22}O_{11} + 12\ O_2 = 12\ CO_2 + 11\ H_2O,$$
$$342.176 + 384 = 528 + 198.176,$$
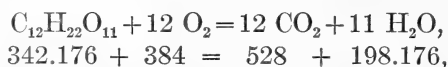
each gram of carbon dioxid is accompanied by the evolution of

$$\frac{342.176 \times 3.96}{528} = 2.5663 \text{ large calories.}[2]$$

To determine the temperature rise, K, of 1 kilogram of fruit for each gram of carbon dioxid formed, it is necessary to divide by the specific heat of the fruit. Assuming the same specific heat of fruit to be that used by refrigeration engineers, 0.9, $K = 2.85°$ C. and k (the temperature rise per milligram of carbon dioxid) $= 0.00285°$ C.

Equation 1 ($\log y = \log y_o + at$) expressing the relation between the respiratory activity and the temperature (see p. 20) may be written

$$y_t = y_o 10^{at}, \tag{2}$$

in which y_t and y_o are the rates of evolution of carbon dioxid per kilogram of fruit per hour at $t°$ and at $0°$, respectively, and a is a constant determined experimentally. Let the time expressed in hours during which the adiabatic conditions are imposed $= T$.

During the first finite interval of time ΔT, e. g., during the first hour after adiabatic conditions are imposed, the activity is approximately expressed by equation 2 and the temperature rise by

$$\Delta t = ky = ky_o 10^{at}, \tag{3}$$

the carbon dioxid per kilogram per hour being expressed in milligrams. As the temperature changes slightly during the first hour in accordance with equation 3, the results are not quite correct. The rate at which the temperature rises at the beginning of the interval ΔT is evidently correctly expressed by equation 3.

Therefore

$$\frac{dt}{dT} = ky_o 10^{at}.$$

On integrating, $T = \dfrac{1}{ky_o}\displaystyle\int_{t'}^{t''} 10^{-at} dt = -\dfrac{1}{ky_o a \log_e 10} 10^{-at} \Big|_{t'}^{t''}$

$$= \frac{10^{-at'} - 10^{-at''}}{ky_o a \log_e 10},$$

---

[1] Data from U. S. Dept. Agr., Office of Experiment Stations, Bul. 109, p. 17.

[2] The value 2.56 is given as the calorific equivalent of 1 gram of carbon dioxid by Benedict and Carpenter (Carnegie Institution of Washington, No. 126, p. 211).

$$10^{at''} = \frac{10^{at'}}{1 - ky_0 a \, \log_e 10. \; 10^{at'} T}$$

$$t'' = t' - \frac{\log \, (1 - ky_{t'}a \, \log_e 10 \, T)}{a}$$

or

$$t'' = t' - \frac{\log \, (1 - mT)}{a}$$

where

$$m = ky_{t'}a \, \log_e 10.$$

The most difficult part of work of this kind is the selection of the differential; this was done by S. J. Dennis, of the Bureau of Plant Industry, who also aided the author in making the integration.

APPLICATION OF FORMULA TO SPECIFIC CASES.

As an illustration this formula has been applied to the Connett peaches of July 22, which, if they followed exactly van't Hoff's formula, would respire at the rates of 120.5, 53.0, 23.2, and 10.2 mg of carbon dioxid per kilogram per hour at temperatures of 30°, 20°, 10°, and 0° C., respectively—the constants $a = 0.0357$ and $y = 10.2$ having been determined experimentally.

In the following table the increases of temperature with time are shown:

TABLE 5.—*Increase of temperature of Connett peaches, during definite intervals of time when adiabatic conditions are imposed at varying initial temperatures (July 22).*

Interval of time (T).	Temperature of fruit (t'') after given intervals (T), calculated from different initial temperatures (t').			
	$t'=0°$ C. $y=10.2$ $m=0.0024$	$t'=10°$ C. $y=23.2$ $m=0.0054$	$t'=20°$ C. $y=53.0$ $m=0.0124$	$t'=30°$ C. $y=120.5$ $m=0.0282$
Hours.	°C. (t'').	°C. (t'').	°C. (t'').	°C. (t'').
1	0.03	10.07	20.15	30.35
10	.3	10.7	21.6	34.0
20	....	....	23.5	40.1
30	....	....	25.7	52.9
35	....	....	....	84.2
40	....	....	28.4	....
50	1.6	13.9	31.8	....
60	....	....	36.6	....
70	....	....	44.7	....
80	....	....	80.0	....
100	3.3	19.6	....	....
140	....	27.4	....	....
150	5.4	30.6	....	....
160	....	34.9	....	....
170	....	41.5	....	....
180	....	57.1	....	....
200	8.0	....	....	....
250	11.1	....	....	....
300	15.5	....	....	....
350	22.3	....	....	....
360	24.3	....	....	....
370	26.6	....	....	....
380	29.6	....	....	....
390	33.5	....	....	....
400	39.2	....	....	....
410	50.3	....	....	....
415	67.2	....	....	....

The same data are given graphically in figures 16 and 17 (pp. 37 and 38).   The curves and model show that fruits stored under such conditions increase in temperature and in physiological activity more or less rapidly according as they are warm or cool when adiabatic conditions are imposed.   At cold storage or refrigerator temperatures, in case of the example given, the temperature rose 0.3° and 0.7°, respectively, during 10 hours, whereas during the same interval the temperature rose 1.45° and 3.65° when the temperatures at which the fruit was stored were 20° and 30° C., respectively.   It has been suggested that it would be possible to follow the rate of temperature rise of a product about to undergo self-heating by placing a recording thermometer near the center of the material.   If the heating observed was due to the operation of the respiratory activities alone, it is probable that the curve drawn by the recording thermometer would approximate the theoretical curve which could be drawn in advance from a knowledge of the respiratory activity.   It is thus highly probable that this method of calculating the temperature rise and of tracing the theoretical curve will be of value in the investigation of phenomena of self-heating, the causes and mechanism of which are now but little understood.
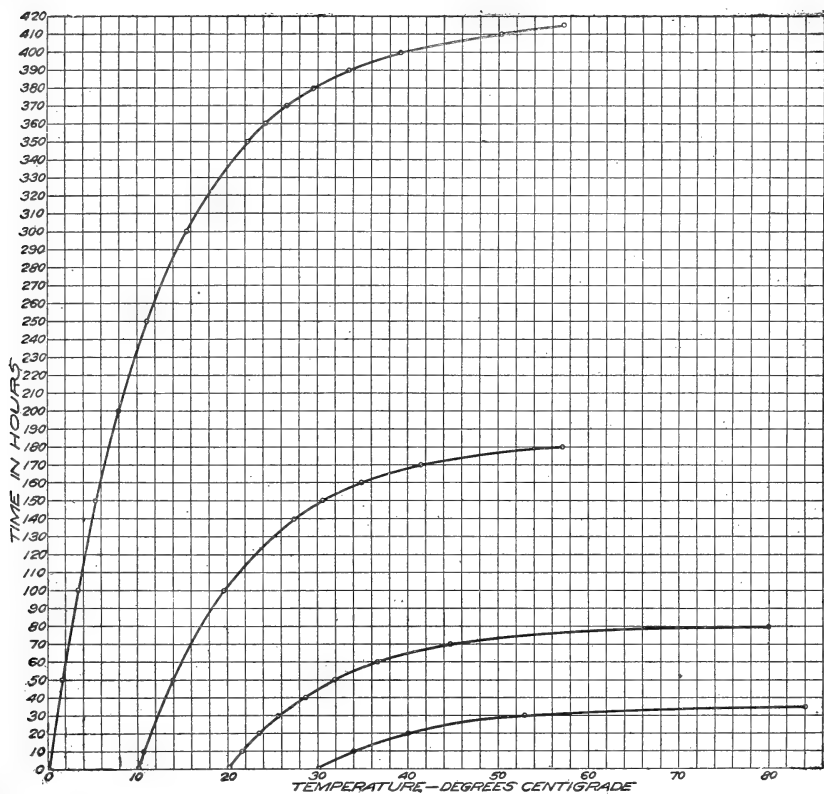
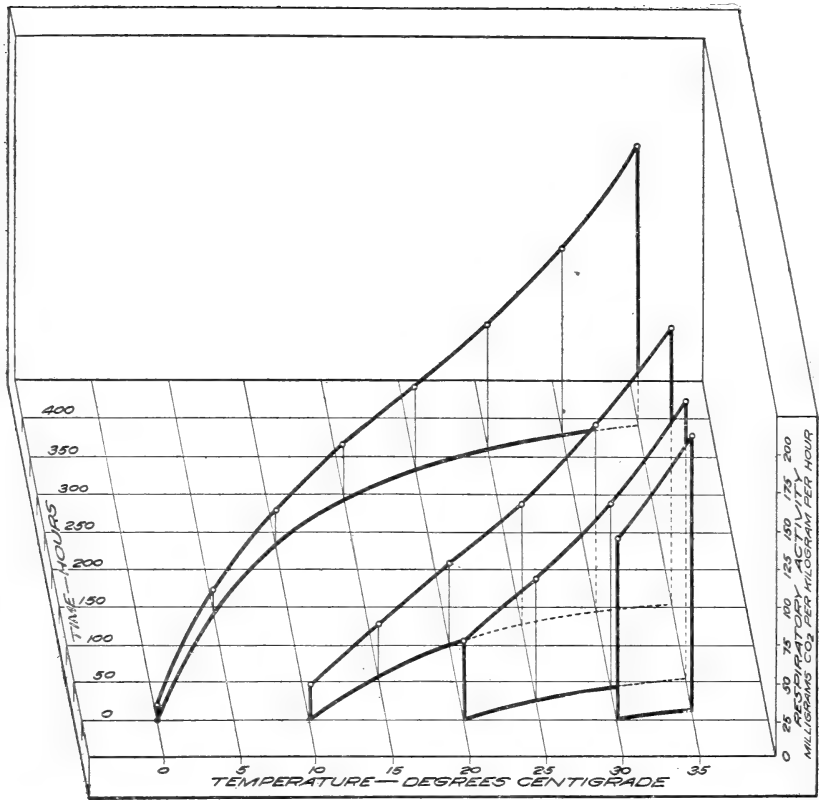FIG. 16.—Theoretical rate of increase in the temperature of fruit held under adiabatic conditions.

FIG. 17.—Theoretical rate of increase in the respiration and temperature of fruit held under adiabatic conditions.

SUMMARY.

(1) An absorption apparatus and a constant-temperature incubator are described suitable for use in the study of the respiration of fruits.

(2) Measurements are given of the rate of respiration at different temperatures of many fruits—berries, peaches, apples, grapes, etc.

(3) The respiratory intensity of these fruits varied greatly, but when the data were plotted similarly shaped curves were formed.

(4) No correlation between composition or size and respiratory activity appeared. In general, however, fruits which grow and mature quickly and soon become overripe respire rapidly. This is true of most of the small fruits. On the other hand, fruits having a long growing season and maturing slowly, as the citrus fruits, are very inactive physiologically. Peaches, plums, apples, pears, and grapes are intermediate in this respect.

(5) When plotted as logarithms, the values expressing the intensity of respiration were found to lie principally along straight lines. A ruled line drawn among the points therefore represented approximately the equation of the relation between respiratory activity and temperature. By construction the form of this equation was $\log y = \log y_0 + at$, in which the constants y_0 and a could be readily determined by inspection. The constant y_0 varied for each kind of fruit. The constant a varied slightly from one fruit to another and was equal to 0.0376 ± 0.00044, the value 0.00044 being the probable error. (See p. 24 for definition of terms.)

(6) The rate of respiration increased from 1.89 to 3.01 times, an average of 2.376 times for each $10°$ rise in temperature for 49 sets of determinations with 40 different kinds of fruits.

(7) The general equation expressing with fair exactness the effect of temperature on the respiration of fruits is

$$\log y = \log y_0 + at,$$

or, in the exponential form,

$$y = y_0 \, 10^{at},$$

where y is the rate of evolution of carbon dioxid expressed as milligrams of carbon dioxid per kilogram of fruit per hour at temperature $t°$ C.; y_0 is the respiration rate at $0°$ C., and $a = 0.0376 \pm 0.00044$.

(8) Three experiments in field studies were carried on in which carbon-dioxid-free air was aspirated through jars containing peaches attached to the tree and detached therefrom, respectively, and the amounts of carbon dioxid given off by the fruit were determined. No stimulus in the rate of respiration, due to picking, could be detected by this method, and it is probable that if such change occurs it is but small.

(9) Assuming that fruits follow the equation given in paragraph 7, that the heat resulting from the respiration and the specific heat of the fruit are known, and that the fruit is held under adiabatic conditions, an equation is derived from which the temperature of fruit t'' may be calculated after a given time T, starting at a known temperature t'. This equation is as follows:

$$t'' = t' - \frac{\log\ (1-m\,T)}{a}$$

where a is the constant from the general equation (page 20); m is the product of several constants ($k y_t$, a, and $\log_e 10$), in which k is the temperature rise accompanying the formation of 1 gram of carbon dioxid from sucrose (equivalent to $0.00285°$ C.), y_t is the respiratory activity of the fruit at $t'°$ C., and $\log_e 10$ equals 2.3026.

O