CRITICAL SPRING TEMPERATURES FOR APPLES IN THE YAKIMA VALLEY, WASH.

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INTRODUCTION

Orchard heating in the apple-growing sections of the West has grown to large proportions during recent years, especially in the State of Washington, where the western apple production is centered.

Interest in the protection of orchards has led to an insistent demand for more accurate information on the subject of damaging temperatures. Just how low the temperature may safely be allowed to go has an important economic bearing in orchard heating. Growers are not convinced that the scale of damaging temperatures now in use covers their needs satisfactorily. There are too many apparent exceptions to the general rules, and it is now evident that the stage of development of the bloom is far more important than generally has been realized. The growers ask, too, that a new scale of damaging temperatures be based, not upon laboratory experiments, but upon results observed under field conditions.

The primary step in an investigation of this kind is to secure accurate records of orchard temperatures. The United States Weather Bureau, through its fruit-frost service, began to secure such records in the spring of 1923. In the spring of 1924 and afterward the work was carried on through a cooperative agreement between the Weather Bureau, the State of Washington, and the county of Yakima. This article summarizes the results of the investigation up to and including the spring of 1926.

NATURE OF THE INVESTIGATION

All temperature records used in this paper were obtained with standard Weather Bureau equipment, consisting of horizontal recording minimum thermometers and special 29-hour thermographs, although in a few instances 7-day thermographs were used. These instruments were exposed in "fruit-region" shelters with the thermometers 4½ feet above the ground. In these respects the instruments and exposures were the same as those used by Young and Cate in similar work on pears in the Rogue River Valley, Oreg. (*1*).

Shelters were placed in the orchard and estimates of damage were made from those few trees immediately surrounding the shelter. At first no attempt was made to divide the tree into upper and lower portions for determining the damage separately in each portion, but later (1925) this was done. After each frost a count of blossoms was made to determine the amount of damage. In some cases a careful orchard examination was all that was necessary to determine that no damage had been done, but in all cases where damage was discovered a count of blossoms was made.

From 100 to 400 blossoms were cut open and examined at each count. A slightly discolored blossom was classed as uninjured if none of the seeds had been killed. The data in this article are based on a total count of 44,596 blossoms, not considering those counted in orchard examinations, during the four years of the work.

Observations were made on several varieties of apples grown in Yakima Valley orchards, the Winesap, Jonathan, Rome Beauty, Newtown, Delicious, Grimes Golden, and Stayman; principally, however, on the five leading commercial varieties, Winesap, Jonathan, Rome Beauty, Newtown, and Delicious.

STAGES OF DEVELOPMENT

In most researches on temperatures that cause injury to fruit only three stages of development have been recognized: 1, Buds closed but showing color; 2, buds in full bloom; and 3, buds where the petals have fallen. Practical experience has shown, however, that this classification is not detailed enough. Too great a range in development and too great a difference in critical temperatures exist between the three stages. It becomes necessary, therefore, to develop a more detailed classification.

A new classification scale, based on careful experiment, has been devised. It not only brings in the desired detail, but also provides that in practically every instance all the fruit buds on any apple tree, regardless of variety, at any given time fall automatically within not more than three stages in the scale; that is, the prevailing stage and the usual shading into immediately adjacent stages.

The new scale:

Stage	Description
1	Fruit buds dormant.
2	Fruit buds breaking open and showing the green tips of emerging leaves.
3	Individual buds discernible in cluster, but tightly massed together.
4	Individual buds widely separated in cluster, but no color showing. Buds are still tightly closed.
5	Center bud showing color; other buds in the cluster breaking open.
6	All fruit buds showing color.
7	Center bud in full bloom; other buds about to open into full bloom.
8	All buds in full bloom.
9	Petals have fallen.
10	Small green fruits.

RELATION OF BLOSSOM AND CLUSTER DAMAGE TO CROP DAMAGE

Apple trees, like most deciduous fruit trees, produce a large amount of bloom that never matures, even under the most favorable conditions. Assuming a moderate to heavy bloom, if 1 fruit bud in 1 cluster in 4 be allowed to mature—the generally accepted rule for artificial thinning of apples in such cases—a practical estimate may be reached as to the amount of overproduction of bloom. If each cluster contains 5 buds, the usual average for most varieties, then if 1 bud in 20 be allowed to reach maturity to produce a full crop, the overproduction of bloom is 95 per cent. In this theoretical case it is obvious that 75 per cent of the clusters also are not allowed to produce mature fruit.

Practically interpreted, this means that 95 per cent of all the individual fruit buds, which also includes 75 per cent of the clusters, can be pinched off without reducing the final crop, provided, however, that the remaining fruit buds and clusters are properly spaced on the tree and that all buds produce mature fruit. Moderate blossom damage can occur without serious reduction in the final crop, since in such cases usually one or more live buds remain in each cluster, unless

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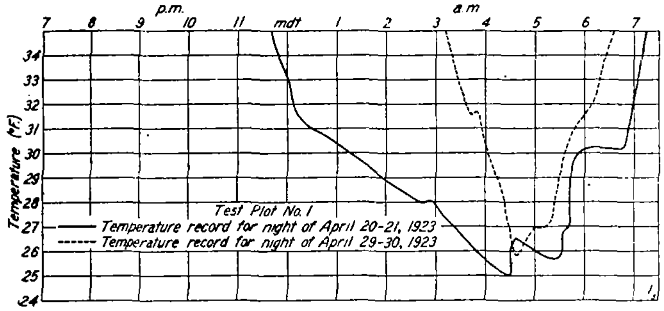

Fig. 1.—The stage of development and the temperature of the dew-point are important factors in determining critical temperatures. The first frost occurred with an evening dew-point of 34° and caused 1 per cent damage to Winesap in Stage 6; the second frost occurred with an evening dew-point of 24° and caused 96 per cent damage to Winesap in Stage 8. Note that the duration of low temperatures with the second frost was much shorter than with the first, although closely the same minimum temperatures were reached. The thermograms in this figure are representative also of the frosts on similar dates in Test Plot No. 2, when damage was caused to Stayman, Grimes Golden, and Delicious

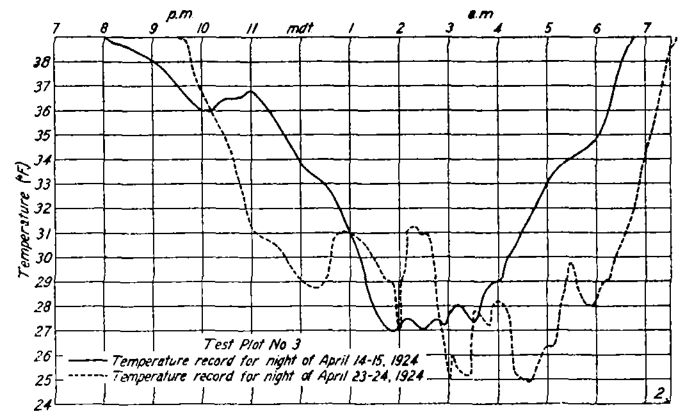

Fig. 2.—These two frosts both occurred with low evening dew-point temperatures. The second frost was more damaging than the first to Winesap and Jonathan, chiefly for three reasons: (1) More advanced stages of development. Blossoms were in Stage 6 on April 15th, and in Stage 8 on April 24th. (2) Longer duration of low temperature and a lower minimum temperature. (3) More rapid rate of rise in temperature in the morning

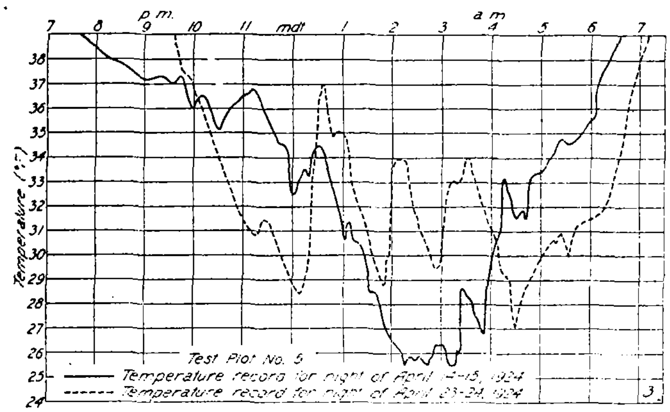

Fig. 3.—The first frost occurred with an evening dew-point temperature of 23° and caused 26 per cent damage to Winesap and 40 per cent damage to Jonathan in Stage 6. The second frost occurred with an evening dew point temperature of 10° and caused only 19 per cent damage to Winesap and no further damage to Jonathan in Stage 8. Judging from the lower dew-point temperature, the more advanced stage of development, and the greater number of hour-degrees of frost with only a slight difference in the minimum temperature, the second frost should have been more damaging than the first. The reason why it was not is evident from the above diagram which shows that the duration at temperatures lower than 30° was longer with the first than with second frost. Another point to be considered is that the first damaging frost usually kills the weaker buds, leaving only buds which sometimes are able to withstand even more severe frost on a later date

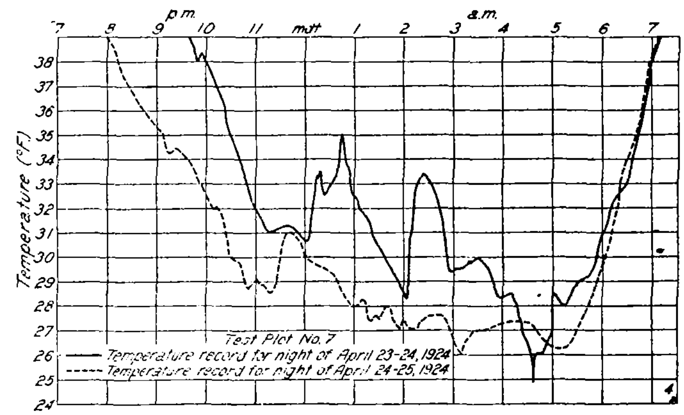

Fig. 4.—These two frosts both occurred with low evening dew-point temperatures. The first frost produced 48 per cent damage to Winesap and 56 per cent damage to Jonathan in Stage 8. The second frost produced no further damage to Winesap and 5 per cent additional damage to Jonathan. In general, the second frost was as severe as the first when the durations of low temperature are considered. Apparently, the first frost killed most of the weaker buds, while the remaining buds were able to endure the shock of a frost, almost equally severe, on the following morning

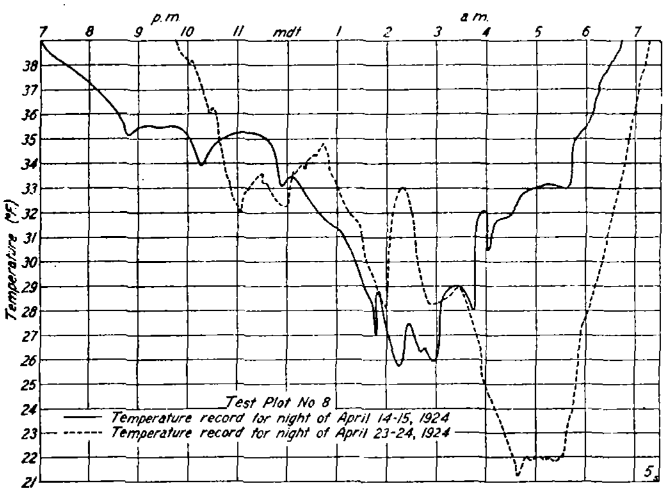

Fig. 5.—These two frosts were responsible for the loss of the crop from Test Plot No. 8. Undoubtedly, the second frost alone would have caused almost total damage. Note especially the rapid rise in temperature after sunrise April 24. When blossoms are frozen, rapid thawing causes the cell walls to rupture and the blossom loses its moisture through evaporation. Two days after this frost the dried-out blossoms were dropping heavily from the trees. The thermograms in this figure are quite representative of temperature conditions on similar dates in Test Plots Nos. 4 and 6

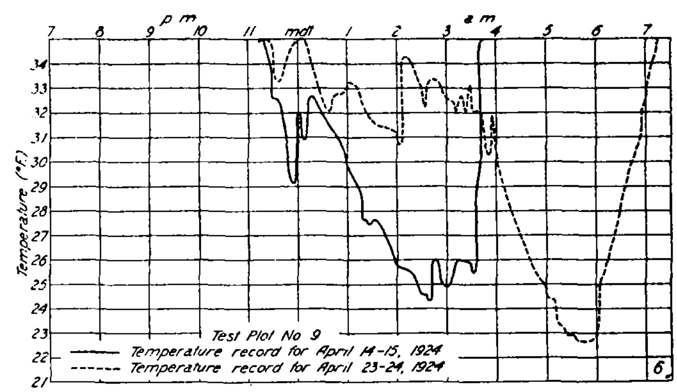

Fig. 6.—The variety is an important consideration when reckoning critical temperatures. The frost on April 15 caused over three times the amount of damage to Delicious in Stage 6 than to Grimes Golden in the same stage. The frost on April 24 killed all remaining live buds of both varieties in Stage 8. Note the rapid rise in temperature in the morning

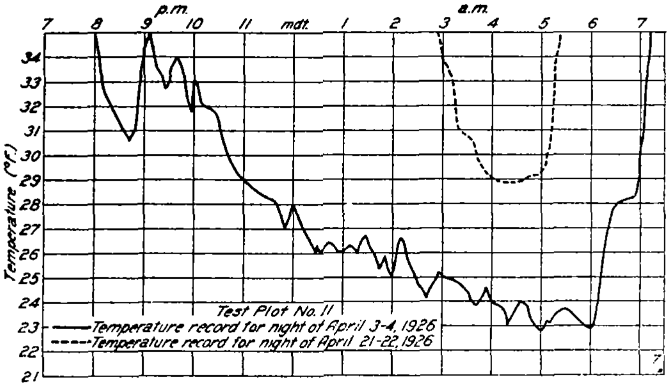

Fig. 7. The most striking example obtained during four years of damaging temperature work, is the fact that severely low temperatures may be endured with little or no damage when the temperature of the dew point is high. Note the lag that occurred in the rate of rise in temperature in the morning. The day, also, was cold, with occasional snow squalls and rain. Compare the damage caused by the frost on April 4, 1926, with the damage caused by the frost on April 15, 1924, in Test Plots Nos. 3 to 9, when a less severe frost, occurring with low dew-point temperature, caused greater damage to apple blossoms in the same stage of development. The frost on April 22 caused some slight damage to Winesap and none to other varieties. The fact that an abnormally heavy drop of Winesap occurred a few days later indicates that the buds were probably in a weakened state and easily damaged by frost

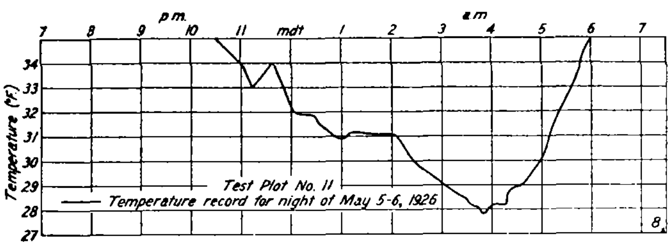

Fig. 8. The only frost of which we have a record that produced damage in Stage 10. In the opinion of the investigators, apples are most easily injured by frost in Stage 9-10, or just after the petals have fallen and before the apples have attained any considerable growth. Newtown apples were not injured by this frost, chiefly because these fruits were of larger size than the other varieties on the test plot

previous frosts have produced heavy blossom damage. Small cluster damage, however, usually means crop damage to some extent, since almost invariably after damage frost-killed clusters predominate in certain portions of the tree, usually on the lower limbs or along certain sections of individual branches. A fruit cluster is damaged when all the buds that comprise it have been killed, since, at most, each cluster is only allowed to produce one fruit.

It is only by considering blossom damage in connection with cluster damage and with due regard to the amount of damage previously done that the extent of crop injury may be correctly judged. For the purposes of this study the amount of blossom damage is the important consideration, as we are chiefly concerned with the critical temperatures of the blossoms themselves.

HOW FROSTS ARE DESCRIBED IN THIS STUDY

We give the date of occurrence, the minimum temperature, the total length of time the temperature remained at and below 32.5° F. (denoted as hours of frost by the symbol H. F. in the tables), and the temperature of the dew point, ° F., at 4:40 p. m. on the preceding day (denoted in the tables by D. P.). In cases of unusual interest we present an enlarged thermograph trace to augment the tabulated data.

Temperature data listed in the tables do not fully describe the temperatures endured by the blossoms under observation. The hours of frost and the minimum temperature can serve only as rough indexes in indicating the severity of frost. Fluctuations in temperatures and minor changes in the rate of fall after the freezing point has been reached may cause greater differences in the duration of temperature at temperature levels lower than 32.5° than would be indicated by the actual duration at 32.5°. See Figure 3 for an illustration of this condition.

The most severe frost it is possible to conjecture is one where the duration at the minimum temperature is exactly the same as the duration at the freezing point. Such a condition never occurs in nature. The closer a given frost approaches this limiting condition, however, the more severe it must be regarded. Thermograms, therefore, are quite necessary to accurately describe frosts. Lack of space unfortunately prevents the inclusion in this study of thermograms for each frost listed in the tables. A few of the more important cases have been selected for which thermograms are presented, in order that these frosts may be accurately described.

DISCUSSION OF PROBLEM

Many factors bear on the amount of damage caused by frost and make the determination of critical temperatures an exceedingly complex matter. These factors, enumerated and briefly discussed, are:

1. *State of weather preceding frost.*—Blossoms are tender apparently, when the previous weather has been such as to cause rapid advancement in bloom.
2. *Vitality.*—Weak blossoms are injured more easily by frost than strong blossoms. See Figure 7.
3. *Variety.*—Some varieties of apples are more susceptible to frost injury than others. See Figure 6.
4. *Stage of development of blossoms.*—The more advanced the stage of development the more susceptible are the blossoms to frost injury. See Figure 1. An exception to this rule occurs in Stage 10, when the apples are beginning to take on size. The larger fruits are not as easily killed as the smaller ones. See Figure 8.
5. *Amount of previous frost damage.*—The first damaging frost usually kills the weaker buds, and sometimes leaves buds which are able to withstand even more severe frost on a later date. See Table 2, test plot No. 5, Winesap, April 24 and 25, 1924. See also Figures 3 and 4.
6. *Severity of the frost.*—Other conditions being the same, the lower the minimum temperature and the longer the duration at low temperatures the more damaging the frost usually proves to be. See Figures 1, 2, and 3.
7. *Temperature of the dew point.*—Other conditions being the same, greater damage almost invariably occurs when the evening dew-point temperature is low than when it is high. See Figures 1 and 7.
8. *Rate of rise in temperature following the frost.*—When plant tissue is frozen, rapid thawing releases moisture faster than it can be reabsorbed by the tissue. The plant cells are then ruptured and killed. When the thawing is gradual the plant tissue may be able to take up the moisture as fast as it is released. The plant cells then remain intact and alive. When blossoms are frozen the damage may be great or small, depending on the rate at which thawing is accomplished. See Figures 5, 6, and 7.

NOTES ON THE SERIES OF OBSERVATIONS

Spring of 1923.—Apples bloomed from two to three weeks later than usual, owing to cold and unfavorable growing weather. Due to the lateness of the season frost did little damage in the Yakima Valley apple orchards as a whole, and good crops were harvested quite generally.

Observations were made on two test plots, both located in the same orchard in about the coldest part of the large

Wide Hollow draw. This orchard had never proved profitable, and consequently was being given only nominal attention. Care was taken, however, to select for our work only trees that seemed healthy and vigorous. During the summer and fall of 1923 the orchard was cut down by the owner as a climax to his unprofitable venture, thus making a final check on the crop difficult to obtain.

Of the seven varieties of apples under observation, all the trees except the Delicious were about 11 years old and bore a light to moderate amount of bloom. The Delicious tree was about 7 years old.

Damaging temperature data secured during this season are presented in Table 1.

TABLE 1.—*Damaging temperature data secured during the spring of 1923*

TEST PLOT NO. 1

Date	Minimum temperature	H. F.	D. P.	Winesap Stage	Winesap Damage to blossoms	Winesap Damage to clusters	Jonathan Stage	Jonathan Damage to blossoms	Jonathan Damage to clusters	Rome Beauty Stage	Rome Beauty Damage to blossoms	Rome Beauty Damage to clusters	Newtown Stage	Newtown Damage to blossoms	Newtown Damage to clusters
1923	°F	H m	°F		%	%		%	%		%	%		%	%
Apr. 4	27.5	5 55	----	4	0	0	4	0	0	3	0	0	4	0	0
8	25.0	6 50	37	4	0	0	4	0	0	4	0	0	4	0	0
9	24.8	6 30	32	4	0	0	5	0	0	4	0	0	4	0	0
10	28.0	5 20	30	5	0	0	5	0	0	4	0	0	4	0	0
13	29.9	1 15	25	5	0	0	5	0	0	5	0	0	5	0	0
14	29.9	6 25	22	5	0	0	5	0	0	5	0	0	5	0	0
18	29.1	5 05	41	5	0	0	6	0	0	5	0	0	5	0	0
19	31.2	0 30	35	6	0	0	6	0	0	6	0	0	6	0	0
21 [1]	25.0	6 50	34	6	1	0	6–7	([2])	0	6	0	0	6	0	0
25	30.2	4 45	29	7	0	0	7	0	0	6	0	0	6	0	0
26	31.0	2 15	33	7	0	0	7	0	0	7	0	0	7	0	0
28	29.2	1 45	33	8	0	0	8	0	0	7	0	0	7	0	0
30 [3]	25.8	2 45	24	8	96	92	8	81	59	8	19	0	8	40	11

TEST PLOT NO. 2

Date	Minimum temperature	H. F.	D. P.	Stayman Stage	Stayman Damage to blossoms	Stayman Damage to clusters	Grimes Golden Stage	Grimes Golden Damage to blossoms	Grimes Golden Damage to clusters	Delicious Stage	Delicious Damage to blossoms	Delicious Damage to clusters
1923	°F.	H m	°F		%	%		%	%		%	%
Apr. 4	27.9	5 30	----	4	0	0	4	0	0	4	0	0
8	26.0	6 30	37	4	0	0	4	0	0	5	0	0
9	25.1	6 30	32	5	0	0	5	0	0	5	0	0
10	27.9	4 20	30	5	0	0	5	0	0	5	0	0
13	30.4	1 15	25	5	0	0	5	0	0	6	0	0
14	30.4	6 00	22	5	0	0	5	0	0	6	0	0
18	29.1	4 45	41	6	0	0	6	0	0	7	0	0
19	31.3	0 15	35	6	0	0	6	0	0	7	0	0
21	25.5	7 00	34	7	22	5	7	10	0	7	88	56
25	31.0	0 50	29	7	0	0	7	0	0	8	0	0
26	32.0	0 10	33	8	0	0	8	0	0	8	0	0
28	28.2	1 40	33	8	0	0	8	0	0	8	0	0
30 [3]	26.1	2 40	24	8	30	11	8	7	2	8–9	12	44

[1] *Winesap.*—Individual blossoms in Stage 7 were damaged. See Figure 1.
[2] Slight.
[3] See Figure 1.

Spring of 1924.—Blossoming took place at about the usual time. There was, however, an unusual number of frosty days from the start of the season until early in May. Several severe frosts occurred during one period of cold weather which began about March 26 and continued until April 2, causing extensive damage to cherries, apricots, and peaches; less damage to pears, and none to apples.

Then followed a period of good growing weather with only a few moderate frosts, until on April 24 an unusually severe radiational freeze began, which continued for two nights in the orchard districts generally and for five nights in the colder orchards. Apples and pears were seriously injured. This damage, when coupled with that caused by the earlier frosts, caused a marked shortage in the 1924 crop of these fruits in the Yakima Valley.

During this season extensive observations were made on seven test plots, all located in the Congdon orchards in the Wide Hollow draw.

Damaging temperature data secured during this season are presented in Table 2.

TABLE 2.—*Damaging temperature data secured during the spring of 1924*

Date	Minimum temperature	H. F.	D. P.	Winesap Stage	Winesap Damage to blossoms	Winesap Damage to clusters	Jonathan Stage	Jonathan Damage to blossoms	Jonathan Damage to clusters	Remarks
				TEST PLOT NO. 3						
1924	°F.	H. m.	°F.		%	%		%	%	
Apr. 4	24.6	4 55	25	5	0	0	6	11	0	Protected with 96 oil-shaving heaters per acre.
5	27.0	5 20	24	5	0	0	6	0	0	
6	32.0	0 30	38	5	0	0	6	0	0	
8	32.1	0 45	33	5	0	0	6	0	0	
11	32.2	0 30	37	5	0	0	6	0	0	
14	29.8	0 50	23	6	0	0	6	0	0	
15	27.0	3 55	23	6	8	0	6	13	7	See Figure 2.
16	30.2	2 50	23	6	0	0	7	0	0	
17	29.0	2 45	26	6	0	0	7	0	0	
19	28.0	5 30	26	7	0	0	7	0	0	
20	28.5	3 50	27	7	0	0	7	0	0	
21	32.0	1 45	29	7	0	0	8	0	0	
24	24.9	7 58	10	8	80	73	8	62	61	Do.
25	26.5	8 00	12	8	0	0	8	0	0	
26	27.2	6 11	17	8	0	0	8	0	0	
27	28.5	5 55	13	8	0	0	8	0	0	About 4 loose boxes of apples per tree were harvested.
May 1	29.5	4 00	23	9	0	0	9	0	0	
4	29.0	4 05	22	9	0	0	9	0	0	
5	27.5	4 20	32	9	0	0	9	0	0	
				TEST PLOT NO. 4						
Apr. 4	24.6	4 15	25	5	0	0	6	0	0	
5	27.0	5 05	24	5	0	0	6	0	0	
6	31.8	1 15	38	5	0	0	6	0	0	
8	32.2	0 25	33	5	0	0	6	0	0	
14	29.5	1 30	23	6	0	0	6	0	0	
15	26.0	3 45	23	6	30	5	6	18	0	See Figure 5.
16	31.3	2 05	23	6	0	0	7	0	0	
17	28.9	2 25	26	6	0	0	7	0	0	
19	27.6	5 20	26	7	0	0	7	0	0	
20	28.0	3 55	27	7	0	0	7	0	0	
21	31.0	3 40	29	7	0	0	8	0	0	
24	21.3	8 10	10	8	69	93	8	81	93	Do.
25	23.3	8 25	12	8	0	0	8	0	0	
26	25.0	6 48	17	8	0	0	8	0	0	
27	28.5	6 15	13	8	0	0	8	0	0	About ¼ loose box of apples per tree was harvested.
May 1	29.5	2 55	23	9	0	0	9	0	0	
4	28.8	4 15	22	9	0	0	9	0	0	
5	27.5	4 25	32	9	0	0	9	0	0	
				TEST PLOT NO. 5						
Apr. 4	25.4	3 45	25	5	3	0	6	0	0	Protected with eighty 10-quart lard-pail oil heaters per acre.
5	27.9	4 55	24	5	0	0	6	0	0	
11	32.3	0 10	37	6	0	0	6	0	0	
14	30.5	0 40	23	6	0	0	6	0	0	
15	25.5	3 50	23	6	26	8	6	40	1	See Figure 3.
16	31.3	2 00	23	6	0	0	7	0	0	
17	29.0	2 25	26	6	0	0	7	0	0	
19	28.0	5 15	26	7	0	0	7	0	0	
20	28.5	3 50	27	7	0	0	7	0	0	
21	31.0	3 25	29	7	0	0	8	0	0	
24	27.0	5 40	10	8	19	5	8	0	0	Do.
25	26.0	8 50	12	8	0	0	8	0	0	
26	27.1	6 50	17	8	0	0	8	0	0	
27	28.5	6 15	13	8	0	0	8	0	0	14 loose boxes of apples per tree were harvested.
May 1	29.9	3 00	23	9	0	0	9	0	0	
4	29.3	3 55	22	9	0	0	9	0	0	
5	28.0	3 30	32	9	0	0	9	0	0	
				TEST PLOT NO. 6						
Apr. 4	25.5	3 00	25	5	0	0	6	0	0	
5	27.9	4 50	24	5	0	0	6	0	0	
14	31.3	0 45	23	6	0	0	6	0	0	
15	26.0	3 00	23	6	30	9	6	38	6	See Figure 5.
16	32.0	0 20	23	6	0	0	7	0	0	
17	29.2	2 20	26	6	0	0	7	0	0	
19	28.1	4 40	26	7	0	0	7	0	0	
20	28.4	4 00	27	7	0	0	7	0	0	
21	31.6	2 00	29	7	0	0	8	0	0	
24	23.3	5 45	10	8	67	85	8	59	83	Do.
25	22.0	8 40	12	8	([1])	([1])	8	([1])	([1])	
26	24.9	6 15	17	8	([1])	([1])	8	([1])	([1])	
27	29.0	5 00	13	8	0	0	8	0	0	About ¼ loose box of apples per tree was harvested.
May 1	30.0	3 00	23	9	0	0	9	0	0	
4	28.0	3 00	22	9	0	0	9	0	0	
5	28.5	4 45	32	9	0	0	9	0	0	

[1] Slight.

TABLE 2.—*Damaging temperature data secured during the spring of 1924*—Continued

TEST PLOT NO. 7

Date	Minimum temperature	H. F.	D. P.	Winesap: Stage	Winesap: Damage to blossoms	Winesap: Damage to clusters	Jonathan: Stage	Jonathan: Damage to blossoms	Jonathan: Damage to clusters	Remarks
	° *F.*	*H. m.*	° *F.*		%	%		%	%	
Apr. 3	31.9	1 40	27	5	0	0	6	0	0	Protected with 65 coal briquet heaters per acre.
4	25.6	4 55	25	5	3	0	6	4	1	
5	27.4	5 15	24	5	0	0	6	0	0	
6	32.0	0 50	38	5	0	0	6	0	0	
8	31.9	0 15	33	5	0	0	6	0	0	
11	32.0	0 10	37	5	0	0	6	0	0	
14	30.2	0 45	23	6	0	0	6	0	0	
15	26.8	3 35	23	6	15	1	6	11	0	
16	31.0	1 40	23	6	0	0	7	0	0	
17	29.4	2 25	26	6	0	0	7	0	0	
19	28.2	5 30	26	7	0	0	7	0	0	
20	28.0	3 55	27	7	0	0	7	0	0	
21	30.9	3 25	29	7	0	0	8	0	0	
24	24.8	4 50	10	8	48	39	8	56	33	See Figure 4.
25	26.0	8 20	12	8	0	0	8	5	10	Do.
26	27.0	6 45	17	8	18	15	8	0	0	
27	28.8	6 30	13	8	0	0	8	0	0	
May 1	29.6	4 10	23	9	0	0	9	0	0	About 11 loose boxes of apples per tree were harvested.
4	28.7	4 00	22	9	0	0	9	0	0	
5	28.4	4 10	32	9	0	0	9	0	0	

TEST PLOT NO. 8

Date	Minimum temperature	H. F.	D. P.	Winesap: Stage	Winesap: Damage to blossoms	Winesap: Damage to clusters	Jonathan: Stage	Jonathan: Damage to blossoms	Jonathan: Damage to clusters	Remarks
Apr. 8	32.0	0 40	33	5	0	0	6	0	0	
11	32.3	1 30	37	5	0	0	6	0	0	
14	30.9	1 15	23	6	0	0	6	0	0	
15	25.6	4 10	23	6	25	0	6	17	0	See Figure 5.
16	31.8	1 30	23	6	0	0	7	0	0	
17	29.9	2 00	26	6	0	0	7	0	0	
19	28.5	5 40	26	7	0	0	7	0	0	
20	28.6	4 00	27	7	0	0	7	0	0	
21	32.0	1 10	29	7	0	0	8	0	0	
24	21.3	5 30	10	8	74	93	8	80	90	Do.
25	22.0	8 10	12	8	0	0	8	1	5	
26	24.8	6 55	17	8	0	0	8	1	1	
27	28.5	6 15	13	8	0	0	8	0	0	About ¼ loose box of apples per tree was harvested.
May 1	30.0	4 00	23	9	0	0	9	0	0	
4	29.0	4 00	22	9	0	0	9	0	0	
5	28.7	2 00	32	9	0	0	9	0	0	

TEST PLOT NO. 9

Date	Minimum temperature	H. F.	D. P.	Delicious: Stage	Delicious: Damage to blossoms	Delicious: Damage to clusters	Grimes Golden: Stage	Grimes Golden: Damage to blossoms	Grimes Golden: Damage to clusters	Remarks
Apr. 7	------	----------	----	4	6	0	5	7	0	Damage probably occurred on April 4, under conditions similar to those on test plot No. 6.
14	30.9	0 45	23	5	0	0	5	0	0	
15	24.3	3 30	23	6	83	73	6	27	29	See Figure 6.
16	31.2	2 00	23	6	0	0	6	0	0	
17	30.0	1 45	26	6	0	0	6	0	0	
19	29.2	5 15	26	6	0	0	6	0	0	
20	28.2	4 15	27	6	0	0	7	0	0	
21	29.9	1 45	29	7	0	0	7	0	0	
24	22.7	4 00	10	7	11	27	7	63	71	See Figure 6. No apples were harvested.

Spring of 1925.—The season was about two weeks earlier than usual in the Yakima Valley. Nevertheless, very little frost occurred and no low minimum temperatures. In all parts of the valley frost damage was at a minimum, artificial thinning of all fruits except Bartlett pears was necessary, and full crops were produced.

Observations were taken on one test plot in the Wide Hollow section. This plot was selected because five varieties of apples and two varieties of pears were grown within its small area. An attempt was made to determine separately the damage in the upper and lower branches.

Damaging temperature data secured during this season are presented in Table 3.

TABLE 3.—*Damaging temperature data secured during the spring of 1925, from test plot No. 10*

Date	Minimum temperature	H. F.	D. P.	Winesap: Stage	Winesap upper branches: Damage to blossoms	Winesap upper branches: Damage to clusters	Winesap lower branches: Damage to blossoms	Winesap lower branches: Damage to clusters	Rome Beauty: Stage	Rome Beauty upper branches: Damage to blossoms	Rome Beauty upper branches: Damage to clusters	Rome Beauty lower branches: Damage to blossoms	Rome Beauty lower branches: Damage to clusters
1925	° *F.*	*H. m.*	° *F.*		%	%	%	%		%	%	%	%
Apr. 17	29.9	3 30	52	7	0	0	0	0	6	0	0	0	0
19	28.4	7 25	41	7	0	0	0	0	6	0	0	0	0
20	28.3	5 40	35	7	0	0	0	0	6	0	0	0	0
22	29.5	3 25	36	8	0	0	0	0	7	0	0	0	0
23	31.0	1 15	28	8	0	0	0	0	7	0	0	0	0
24	31.9	0 15	31	8	0	0	0	0	7	0	0	0	0
26	29.0	2 40	32	8	0	0	0	0	7	0	0	0	0
27	30.2	1 50	33	8	0	0	0	0	8	0	0	0	0
28	27.1	6 40	25	9	16	0	18	0	8	0	0	1	0
29	32.0	0 10	31	9	0	0	0	0	8	0	0	0	0
May 3	30.0	1 05	36	9	0	0	0	0	9	0	0	0	0
4	32.0	1 25	26	9	0	0	0	0	9	0	0	0	0

Date	Minimum temperature	H. F.	D. P.	Newtown: Stage	Newtown upper branches: Damage to blossoms	Newtown upper branches: Damage to clusters	Newtown lower branches: Damage to blossoms	Newtown lower branches: Damage to clusters	Delicious: Stage	Delicious upper branches: Damage to blossoms	Delicious upper branches: Damage to clusters	Delicious lower branches: Damage to blossoms	Delicious lower branches: Damage to clusters
Apr. 17	29.9	3 30	52	6	0	0	0	0	7	0	0	0	0
19	28.4	7 25	41	7	0	0	0	0	7	0	0	0	0
20	28.3	5 40	35	7	0	0	0	0	7	0	0	0	0
22	29.5	3 25	36	7	0	0	0	0	8	0	0	0	0
23	31.0	1 15	28	8	0	0	0	0	8	0	0	0	0
24	31.9	0 15	31	8	0	0	0	0	8	0	0	0	0
26	29.0	2 40	32	8	0	0	0	0	8	0	0	0	0
27	30.2	1 50	33	8	0	0	0	0	8	0	0	0	0
28	27.1	6 40	25	9	30	4	43	3	9	1	0	8	0
29	32.0	0 10	31	9	0	0	0	0	9	0	0	0	0
May 3	30.0	1 05	36	9	0	0	0	0	9	0	0	0	0
4	32.0	1 25	26	9	0	0	0	0	9	0	0	0	0

REMARKS.—A Bartlett pear tree in the test plot endured all frosts without damage. Blossoms in full bloom on Apr. 14; petals falling on Apr. 23; small green pears one-eighth to three-eighths inches in diameter were set on Apr. 27. Full crops were harvested from all trees.

Spring of 1926.—The season was about two weeks earlier than usual in the Yakima Valley. A number of moderate frosts during the latter part of March caused only nominal damage to the valley fruit crop as a whole. On April 4, 1926, a severe radiational frost heavily damaged cherries, prunes, and apricots, but, strangely enough, did very little damage to apples and pears. Later in the season there was a heavy natural drop of Winesap, especially severe in the upper valley, probably due to the number of cold days during the blossoming period for Winesap in the upper valley, which might have prevented pollination. A number of frosty mornings early in May caused some damage to practically all varieties of apples, mostly by frost-marking the skin. There was very little rain during the entire spring season.

Observations were taken on the same test plot used in the spring of 1925. Damaging temperature data secured in 1926 are listed in Table 4.

TABLE 4.—*Damaging temperature data secured during the spring of 1926 from test plot No. 11*

Date	Minimum temperature	H. F.	D. P.	Winesap: Stage	Winesap, Upper branches: Damage to blossoms	Winesap, Upper branches: Damage to clusters	Winesap, Lower branches: Damage to blossoms	Winesap, Lower branches: Damage to clusters	Jonathan: Stage	Jonathan, Upper branches: Damage to blossoms	Jonathan, Upper branches: Damage to clusters	Jonathan, Lower branches: Damage to blossoms	Jonathan, Lower branches: Damage to clusters	Rome Beauty: Stage	Rome Beauty, Upper branches: Damage to blossoms	Rome Beauty, Upper branches: Damage to clusters	Rome Beauty, Lower branches: Damage to blossoms	Rome Beauty, Lower branches: Damage to clusters	Newtown: Stage	Newtown, Upper branches: Damage to blossoms	Newtown, Upper branches: Damage to clusters	Newtown, Lower branches: Damage to blossoms	Newtown, Lower branches: Damage to clusters	Delicious: Stage	Delicious, Upper branches: Damage to blossoms	Delicious, Upper branches: Damage to clusters	Delicious, Lower branches: Damage to blossoms	Delicious, Lower branches: Damage to clusters
1926	° F.	H. m.	° F.		%	%	%	%		%	%	%	%		%	%	%	%		%	%	%	%		%	%	%	%
Mar. 25	26.9	7 20	19	4	12	4	14	4	4	1	0	4	0	4	0	0	6	0	4	0	0	0	0	4	2	0	16	0
26	27.9	2 50	25	4	0	0	0	0	4	0	0	0	0	4	0	0	0	0	4	0	0	0	0	4	0	0	0	0
27	27.5	3 10	31	4	0	0	0	0	5	0	0	0	0	4	0	0	0	0	4	0	0	0	0	4	0	0	0	0
29	31.7	1 15	28	5	0	0	0	0	5	0	0	0	0	5	0	0	0	0	5	0	0	0	0	5	0	0	0	0
Apr. 2	26.9	3 45	28	5	0	0	0	0	5	0	0	0	0	5	0	0	0	0	5	0	0	0	0	5	0	0	0	0
4 [1]	22.9	9 50	37	6	2	0	12	1	6	13	0	22	7	6	2	0	1	0	5–6	3	0	1	0	6	59	26	56	38
13	32.3	0 15	32	8	0	0	0	0	8	0	0	0	0	8	0	0	0	0	8	0	0	0	0	8	0	0	0	0
22 [1]	28.9	2 00	39	9	20	0	19	0	9	0	0	0	0	9	0	0	0	0	8	0	0	0	0	9	0	0	0	0
23	29.4	3 00	30	9	0	0	0	0	9	0	0	0	0	9	0	0	0	0	9	0	0	0	0	9	0	0	0	0
24	29.2	4 40	28	9	0	0	0	0	9	0	0	0	0	9	0	0	0	0	9	0	0	0	0	9	0	0	0	0
May 5	29.8	3 35	39	10	0	0	0	0	10	0	0	0	0	10	0	0	0	0	10	0	0	0	0	10	0	0	0	0
6 [2]	27.8	5 30	30	10	A	A	B	B	10	C	C	D	D	10	E	E	F	F	10	0	0	0	0	10	G	G	H	H
7	29.2	3 50	34	10	(3)	(3)	(3)	(3)	10	(3)	(3)	(3)	(3)	10	(3)	(3)	(3)	(3)	10	0	0	0	0	10	(3)	(3)	(3)	(3)
8	28.2	7 30	31	10	(3)	(3)	(3)	(3)	10	(3)	(3)	(3)	(3)	10	(3)	(3)	(3)	(3)	10	0	0	0	0	10	(3)	(3)	(3)	(3)
9	31.0	1 00	38	10	0	0	0	0	10	0	0	0	0	10	0	0	0	0	10	0	0	0	0	10	0	0	0	0
10	31.0	2 00	28	10	0	0	0	0	10	0	0	0	0	10	0	0	0	0	10	0	0	0	0	10	0	0	0	0

[1] See Figure 7.
[2] See Figure 8.
[3] Further frost-marking produced, but extent of damage impossible to determine.

Reference letter	Number fruits examined	Number fruits good	Number fruit seeds killed	Number fruits frost marked
A	44	17	19	8
B	61	17	28	16
C	101	34	16	51
D	69	51	0	18
E	83	14	0	69
F	77	9	0	68
G	10	0	1	9
H	34	5	0	29

Winesap.—A heavy natural drop occurred in near-by orchards during the first 2 weeks in May; other varieties not affected. No thinning was necessary and a light crop was in prospect.
Jonathan.—Frost-marking that occurred during May 6-8 was light. Thinning was necessary and a full crop of good quality fruit was harvested.
Rome Beauty.—Frost-marking that occurred during May 6-8 was light. On May 20 many of the frost-marked fruits apparently had recovered from the effects of previous damage. Thinning was necessary and a full crop was in prospect.
Newtown.—Heavy thinning was necessary and a full crop was in prospect.
Delicious.—Frost-marking that occurred during May 6-8 was very pronounced. Some thinning was necessary and a fair crop was harvested, which was practically all "C" grade, due to frost-marking.

CRITICAL TEMPERATURES

Consideration of the mass of data on damaging temperatures set forth in this paper brings out four important points:

1. It is not possible to name a definite minimum temperature or any specific duration at any given temperature that will produce corresponding amounts of damage to all varieties of apples under all conditions within the range of temperatures that cause damage.
2. The amount of damage caused by any given temperature depends on the amount of water vapor in the air at the time of the frost. There apparently is a correlation between the temperature of the dew point at 4:40 p. m. on the afternoon preceding the frost and the amount of damage caused by the frost.
3. *Greater damage will be caused by a given temperature* when the evening dew point is lower than 32° than when it is higher. The lower the dew point the greater is the amount of damage.
4. Different varieties of apples in the same stage of development are affected to differing degrees by the same frost.

It should be borne in mind, however, that these conclusions, based on a study of records obtained over a period of but 4 years, are tentative only. In the opinion of the writers at least 10 years' observations will be necessary fully to test them. Enough evidence seems to be at hand, however, for formulating at least a roughly approximate scale of damaging temperatures for the different varieties of apples. This evidence will now be summarized.

Stage 1 (dormant stage).—Observational data lacking. Frost damage occurs when minimum temperatures considerably below 0° are experienced. Such damage is spoken of as "winter killing."

Stage 2.—Observational data lacking. Damage to fruit buds rarely occurs, for there is small probability of the damaging temperature being reached after the season has advanced far enough to induce growth in dormant buds. Minimum temperatures that would cause damage in stage 2 probably range from 0° to 10°, depending on the advancement within the stage itself.

Stage 3.—Direct observational data lacking. Damage in stage 3 is rare. It is caused by minimum temperatures that range as low as or lower than 20°. The probable range of damaging temperature for buds in stage 3 is from 10° to 20°, depending on the advancement within the stage itself.

Stage 4.—We have no great quantity of data on damage in this stage. A minimum temperature of 28° with long duration is safe for all varieties of apples, regardless of the dew point. When the dew point is 32° or higher, a minimum temperature as low as 24.8° with a duration at and below 32° of $6^h\ 30^m$ and at 25° of $2^h\ 10^m$ is safely endured by all varieties. When the dew point is 19°, a minimum temperature of 26.9° with a duration at and below 32° of $7^h\ 20^m$ and at 27° of $0^h\ 25^m$ produces limited damage; that is, no commercial damage, to all varieties except Newtown, which will show no damage. The relative susceptibility of the varieties in terms of the amount of blossom damage in this latter case is: Delicious, 16%; Winesap, 13%; Jonathan, 1%; Rome Beauty, 1%; and Newtown, 0%.

Stage 5.—A minimum temperature of 28° for long duration is safe for all varieties, regardless of the dew point. When the dew point is 32° or higher, a minimum temperature of 25.1° with a duration below 32° of 6^h 30^m and at 25° of 0^h 15^m is safe for all varieties. With the same dew point, a minimum temperature of 22.9° with duration below 32° of 9^h 50^m and at 23° for 1^h 10^m produces 1% blossom damage to Newtown, and presumably slightly greater damage to other varieties. This latter condition probably marks the point where damage begins with all varieties.

When the dew point is 25°, a minimum temperature of 25.4° with a duration below 32° of 3^h 45^m and at 25° of 0^h 10^m probably marks the point where damage begins for all varieties.

Stage 6.—A minimum temperature of 29° for long duration is safe for all varieties, regardless of the dew point. A minimum temperature of 28° for two or three hours is probably safe for all varieties, regardless of the dew point.

When the dew point is 32° or higher, a minimum temperature of 25.0° with a duration below 32° of 6^h 50^m and at 25° for 0^h 30^m produces slight damage to Winesap, Jonathan, and presumably to Delicious, Stayman, and Grimes Golden as well, but is safe for Rome Beauty and Newtown. A minimum temperature of 22.9° with a duration below 32° of 9^h 50^m and at 23° for 1^h 10^m produces damage to all varieties. The relative susceptibility in this latter case expressed in terms of blossom damage is: Delicious, 56%; Jonathan, 22%; Winesap, 13%; Rome Beauty, 1%; and Newtown, 1%.

When the dew point is 23°, a minimum temperature of 27.0° with duration below 32° of 3^h 55^m and at 27° for 0^h 10^m produces limited damage to all varieties. As the temperature falls damage increases, until with a minimum temperature of 24.3° with a duration below 32° of 3^h 30^m and at 24° of 0^h 15^m the blossom damage to Delicious is 83% and to Grimes Golden 27%.

When the dew point is 25°, a minimum temperature of 24.6° with a duration below 32° of 4^h 55^m and at 25° of 0^h 15^m produces 11% blossom damage to Jonathan. This probably marks a condition where damage begins with all varieties of apples. With the same dew point, a minimum temperature of 25.6° with a duration below 32° of 4^h 55^m and at 26° of 0^h 20^m produces 4% blossom damage to Jonathan.

Stage 7.—A minimum temperature of 28° with a duration of one hour is safe for all varieties of apples, regardless of the dew point. The safe duration at 28° is probably longer than one hour, but direct evidence is lacking on this point.

When the dew point is 32° or higher, a minimum temperature of 25.0° with a duration below 32° of about 7^h 00^m and at 25° of about 0^h 30^m produces limited damage to some varieties and somewhat extensive damage to others. The relative resistance of the different varieties at these temperatures as expressed in the terms of the amount of blossom damage caused is: Delicious, 88%; Stayman, and presumably its near relative, Winesap, 22%; Grimes Golden, 10%; and Jonathan, about 2%. Rome Beauty and Newtown are presumably not injured to an extent greater than Jonathan, but direct evidence is lacking on this point.

When the dew point is 10°, a minimum temperature of 23.0° with a duration below 32° of 4^h 00^m and at 23° of 0^h 30^m produces 100% damage to Delicious and Grimes Golden, and probably serious damage to other varieties.

Stage 8.—A minimum temperature of 29° with a duration of over five hours is safe for all varieties, regardless of the dew point. When the dew point is 32° or higher, a minimum temperature of 28° with a duration of two or three hours is probably safe for all varieties. Limited damage would probably be caused by a minimum temperature of 27° enduring for one hour, although direct evidence is lacking on this point.

When the dew point is very low, ranging from 10° to 13°, a minimum temperature of 27.0° with a duration below 32° of 6^h 00^m and at 27° of only 0^h 05^m causes about 58% blossom damage to Winesap, and probably heavy damage to other varieties. Within the same range of dew point, a minimum temperature of 24.9° with a duration below 32° of 8^h 00^m and at 25° for 1^h 00^m causes 80% damage to Winesap and Jonathan, while with a shorter duration at 25° (0^h 05^m) slightly less damage is produced. Within the same range of dew point, a minimum temperature of 23.3° with a duration below 32° of 5^h 00^m and at 23° for 0^h 05^m produces 100% damage to Winesap and Jonathan, and probably to Stayman, Grimes Golden, and Delicious as well, and serious if not total damage to Rome Beauty and Newtown

When the dew point is 17°, a minimum temperature of 27.0° with a duration below 32° of 6^h 45^m and at 27° of 0^h 20^m produces about 33% damage to Winesap and limited damage to Jonathan. This condition is probably very near the point at which damage begins with all varieties.

When the dew point is 24°, a minimum temperature of 25.8° with a duration below 32° of 3^h 00^m and at 26° for 1^h 00^m produces 100% damage to Winesap, probably also to Delicious and Stayman; serious, but not total damage to Jonathan; 40% damage to Newtown; and 19% damage to Rome Beauty, and probably also to Grimes Golden.

Stage 9.—A minimum temperature of 29° with a duration of over 1 hour is safe for all varieties, regardless of the dew point. When the dew point is 32° or higher, a minimum temperature of 28° with a duration of 30 minutes is safe for all varieties. A minimum temperature of 27° with a duration of 30 minutes and with a dew point of 32° or higher is probably the point at which damage begins with all varieties.

When the dew point is 24°, a minimum temperature of 26.1° with a duration below 32° of 2^h 40^m and at 26° of 0^h 10^m produces nearly 100% damage to Delicious, probably also to Winesap and Stayman; and presumably serious, if not total, damage to all other varieties.

When the dew point is 25°, a minimum temperature of 27.1° with a duration below 32° of 6^h 40^m and at 27° of 0^h 25^m produces 43% damage to Newtown; 10% damage to Winesap; and 8% damage to Delicious. This probably marks the point where damage begins with all varieties.

Stage 10.—We have no great amount of information on damage in stage 10. A minimum temperature of 30° with a duration of 30 minutes appears to be safe for all varieties, regardless of the dew point. With the dew point ranging from 30° upward, a minimum temperature of 29° with a duration of 30 minutes probably defines a condition under which damage begins with most varieties of apples in stage 10.

When the dew point is 32° or higher, a minimum temperature of 29.2° with a duration below 32° of 3^h 50^m and at 29° for 1^h 10^m caused some frostmarking to all varieties except Newtown. The relative susceptibility to damage of the different varieties under this condition can be

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expressed in this order: 1, Delicious; 2, Rome Beauty; 3 Jonathan; 4, Winesap; 5, Newtown.

When the dew point ranges between 30° and 31°, a minimum temperature of 27.8° with a duration below 32° of 5^h 30^m and at 28° of 1^h 10^m produces damage to all varieties except Newtown. This damage is of two kinds—(1) where the seeds are killed, and (2) where the skin is frostmarked but the seeds are not killed. Either type of damage, however, is commercial damage. The relative susceptibility to damage of the different varieties under this condition as expressed on a scale of the number of fruits damaged is: Delicious, 89%; Rome Beauty, 85%; Winesap, 70%; Jonathan, 50%; and Newtown, 0%.

CONCLUSIONS

While the observations on which this study is based cover a period of four spring seasons only, the mass of evidence is sufficiently great to enable these generalizations to be made:

1. The temperature of the dew point at the time of the frost, which can be correlated with the temperature of the dew point at 4.40 p. m. on the afternoon preceding the frost, is too important a factor to be neglected; any accurate scale of critical temperatures for apples must take it into consideration. The data are mere chaos if the dew-point factor be neglected; when it is considered, the evidence fits nicely into an ordered system. Herein, we believe, lies the reason for the dissatisfaction of the growers with the old scales of critical temperatures, for these scales took no account of the amount of water vapor in the air.

Evidence in this paper shows unmistakably that the dew point at the time of the frost has a very important bearing on the amount of damage that will be caused by low temperature. When the dew point is 32° when the air temperature reaches 32°, and the dew point falls as the temperature falls, severely low minimum temperatures can be endured with but slight damage, whereas the same temperature conditions with a low dew point will cause very severe damage. Comparison of the frost on April 4, 1926, in test plot No. 11 with the frost on April 15, 1924, in test plot No. 7, brings out this point in a forceful manner. On April 4, 1926, occurred a minimum temperature of 22.9°. The temperature remained 9^h 50^m below 32° with a duration of 1^h 10^m at 23° with an evening dew point of 37°. On April 15, 1924, occurred a minimum temperature of 26.8°. The temperature remained 3^h 55^m below 32° with a duration of only 0^h 20^m at 27° with an evening dew point of 23°. In each case there was observed relatively the same amounts of damage to Winesap in stage 6.

It is highly probable that one of the reasons such great damage occurs with low dew-point temperature is to be found in the simple relation that exists between the temperature of the dew point and the rate at which the air temperature rises following a frost. As a general rule, the lower the dew-point temperature, the faster is the rate of rise in air temperature after sunrise.

2. Many conditions define the point at which damage begins with apples in the different stages of development. These conditions are made up of several different factors, chief among which are (1) the temperature of the dew point, and (2) the duration of temperature at different temperature levels below 32°. Other factors, too, bear on the amount of damage that will be caused by any damaging temperature conditions, chief among which are (1) the rate of rise in temperature after sunrise, and (2) the vitality of the individual tree. The scale of critical temperatures, therefore, necessarily must be complex, and judgment will be required for its practical application.

3. Different varieties of apples show different degrees of resistance to frost. Furthermore, each variety seems to have a particular stage or stages of development wherein it is particularly susceptible to injury. Thus, for instance, Delicious and Winesap show relatively the same measure of resistance to a given condition in the earlier stages of development, but in later stages Delicious proves to be more tender than Winesap.

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LITERATURE CITED

(1) YOUNG, F. D. AND CATE, C. C. DAMAGING TEMPERATURES AND ORCHARD HEATING IN THE ROGUE RIVER VALLEY, OREGON. Monthly Weather Review, December, 1923, 51: 617–639.

F. M. EXNER ON DYNAMICAL METEOROLOGY

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The state of the atmosphere in respect to what is commonly thought of as weather is completely specified by the six meteorological elements (temperature, pressure, humidity, wind, cloud, and precipitation), which in turn are fully determined by seven physical quantities, viz, temperature, pressure, density, the three components of wind velocity, and the joint mass of solid, liquid, and gaseous water per unit mass of atmosphere. All these seven are dynamical or thermodynamical variables; and hence meteorology, regarded (in accordance with modern tendency) as restricted to the investigation of weather phenomena purely, may be defined as the dynamics and thermodynamics of the earth's atmosphere. And it is with the investigation of weather considered as a dynamical and thermodynamical process that the volume here to be reviewed is concerned.

Weather phenomena are in general so complex and irregular that even a purely empirical understanding of them was very slow to develop; and, although we can not doubt that they are only manifestations of ordinary physical laws, the intricate manner in which a great multitude of influences simultaneously operate to bring about the final result makes it a task of extreme difficulty to bring the facts of daily weather into direct relation with physical principles. Consequently we still are forced to rely extensively upon empirical and statistical