(*-*)
Citrus Station Mimeo Series 62-6
September 19, 1961

Controlled Freezing of Orange Trees and Fruit

I. Response of Orange Trees and Fruits to Freezing Temperatures

C. H. Hendershott

Injury of citrus fruits and trees by unusually cold weather has resulted in considerable economic loss to growers in the past and is one of the important problems the industry must take into account. Although it is impossible to obtain accurate data as to the amount of loss incurred by the citrus industry from freezes, it is generally concluded that the loss is great enough to fully warrant investigation of factors promoting and maintaining cold tolerance of citrus. The heavy loss of fruit from the freeze of 1957-58 led to the initiation of an investigation of freeze injury on citrus to determine what effect various temperatures and durations of time would have on the foliage, fruit and wood of the trees, and on their subsequent behavior. This paper presents data on the cooling rate, temperatures reached and subcooling of oranges artificially frozen on trees, together with after effects of the cold on tree response.

Materials and Methods

To facilitate work on this project, a portable freeze chamber 25 ft. in diameter and 25 ft. in height was constructed capable of exposing a mature citrus tree with its crop of fruit to any desired temperature (Fig. 1).

The chamber has a 15 h.p. commercial compressor mounted on top capable of maintaining a temperature of 15° ± 0.5° F. for an indefinite period of time against an outside temperature of 95° F. Cold air from the expansion coil enters the chamber at the top and is removed at the bottom. The inside air (15,000 cu. ft.) is circulated approximately every minute.

The freezing chamber was erected around the tree during the day, and copper-constantan thermocouples were placed inside the fruits, selected at random, for a constant check on fruit temperature. The thermocouples were usually thrust into the fruit to a depth half-way between the peel and the center of the fruit. One thermocouple was used for recording air temperature inside the chamber, leaving 19 available to measure fruit temperatures on each tree. Leed wires of the thermocouples were attached to a Minneapolis-Honeywell, 20-point recording potentiometer, which recorded the temperature of each fruit every 5 minutes.

Work on this problem was begun in the field during the winter of 1960-61. A total of 12 mature Pineapple trees and 14 mature Valencia trees were exposed to various temperatures for time intervals varying from 4 to 11 hours.

Florida Citrus Commission and
Florida Citrus Experiment Station,
Lake Alfred, Florida.
1048 b - 9/19/61 - CHH

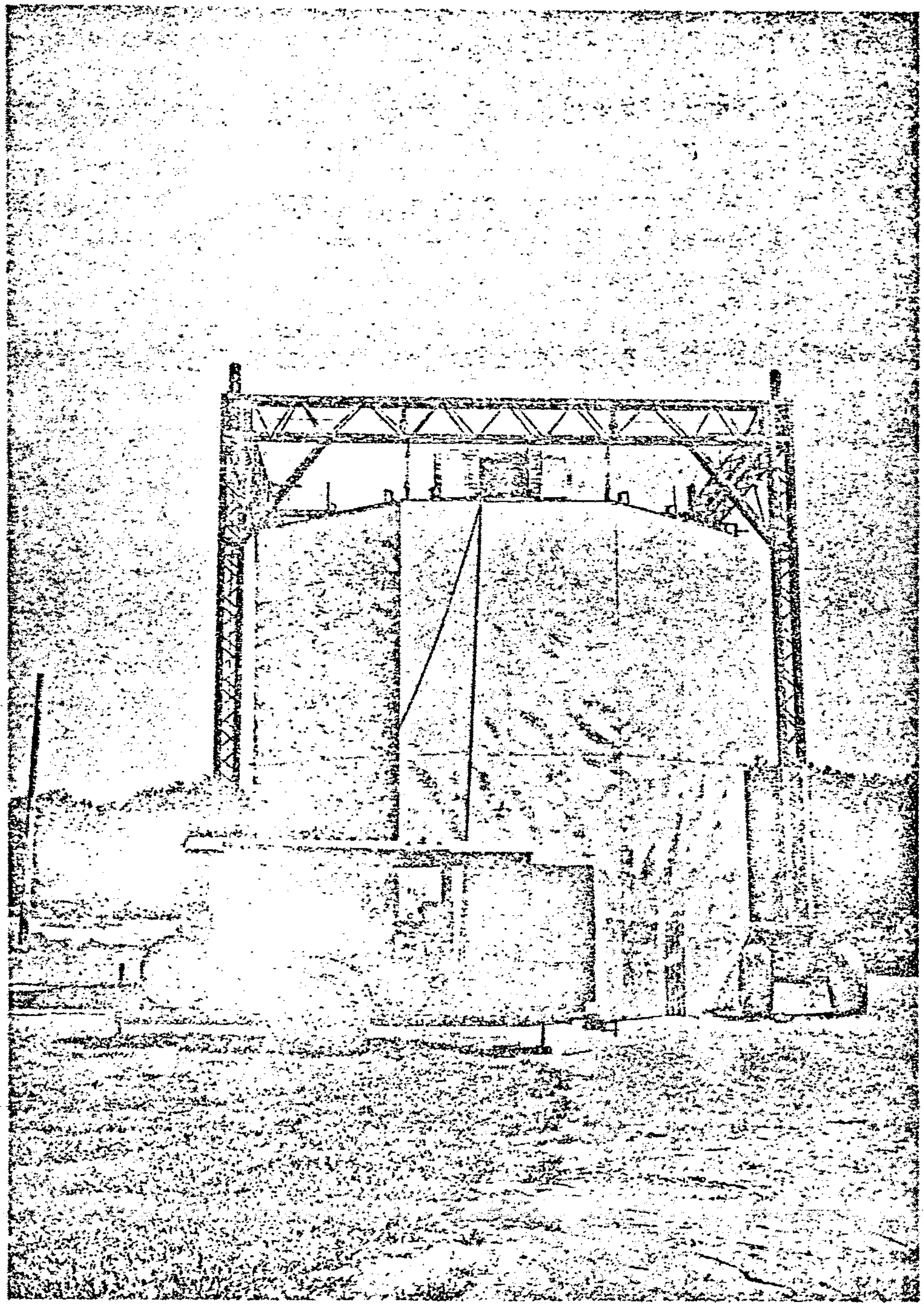

Fig. 1. Portable freeze chamber used for exposing mature citrus trees to freezing temperatures.

Results

Effect of a constant 26° F. on cooling rate of orange fruits. - On the night of January 24, 1961, a Pineapple orange tree was exposed to 26° ± 0.5° F. for 11.25 hours. The box or freeze chamber temperature was lowered from 65° F. to 28° F. in 3.5 hours and held at this temperature until the fruits had cooled to 28.5-30° F. (average 29.2° F.). The box temperature was then lowered to 26° F. for 11.25 hours.

When the box temperature was held at 28° ± 0.5° F. and fruit temperatures ranged from 35-40° F., the cooling rate of the fruits varied from 4.5-7° F. per hour, but as the fruits cooled to 30-34° F., the range in cooling rate dropped to 2-3° F. per hour (Fig. 2). There was apparently no correlation between fruit size and rate of temperature drop since large fruits cooled at the same rate as small fruits, maintaining practically the same temperature differential as was present initially. When the freeze chamber temperature was lowered to 26° ± 0.5° F., the cooling rate of fruits ranged from 1.5-2.5° F. As the fruit temperature approached box temperature the cooling rate decreased to 0.5-1° F. per hour with a 2° F. differential between the fruit and box temperatures (Fig. 2).

When fruit temperatures initially ranged from 28.5-30.5° F. and the air temperature was 3 to 5° F. colder, 3 hours and 50 minutes elapsed before the first orange froze, as indicated by a sudden rise in temperature (Table 1). Freezing of isolated fruits was gradual over the remainder of the experiment. When the experiment was terminated after 11.25 hours at 26° F., 42 per cent of the fruits were unfrozen but in a subcooled state (Table 1).

The freezing point of the juice, as indicated by the maximum temperature obtained after freezing, ranged from 27.5-29° F. with the majority of the fruits being at 28-29° F. (Table 1). This compares favorably with observations of the U. S. Weather Bureau (2) which reported the temperature inside a fruit at which freezing began to be 28.5-29.5° F. for green oranges; 28-29° F. for half-ripe oranges and 27-28° F. for ripe oranges.

Effect of constant 25° F. on cooling rate of orange fruits. - A Pineapple orange tree was exposed to 25° ± 0.5° F. for 8.5 hours on the night of January 18, 1961. At the beginning of the test, fruit temperatures ranged from 60-64.5°F. (average 61.4° F.) with an air temperature of 64° F. The temperature decrease was begun in the afternoon and approximately 3 hours later the air temperature inside the box was 28° ± 0.5° F.; however, fruit temperatures ranged from 37.5-40.5 (average 38.7° F.). Maintaining a box temperature of 28° F. for 2 hours resulted in a decrease in fruit temperatures to 29-30.5° F., or an average rate of decrease of 4-5° F. per hour. The box temperature was gradually lowered during the next 3 hours to 25° ± 0.5°F., an average temperature drop of 1° F. per hour. When the chamber temperature reached its minimum (24.5° F.), fruit temperatures ranged from 24.5-25° F. and 5 per cent of the fruit had frozen. Fruit freezing was gradual throughout the remainder of the night. The test was terminated after holding the air temperature for 8.5 hours at 25° ± 0.5° F. after which 80 per cent of the fruits were frozen (Fig. 3). Therefore, 20 per cent of the fruits had remained in a subcooled state at 25.5-26.5° F. for 8.5 hours.

Florida Citrus Commission and
Florida Citrus Experiment Station,
Lake Alfred, Florida.
1048 c - 9/19/61 - CHH

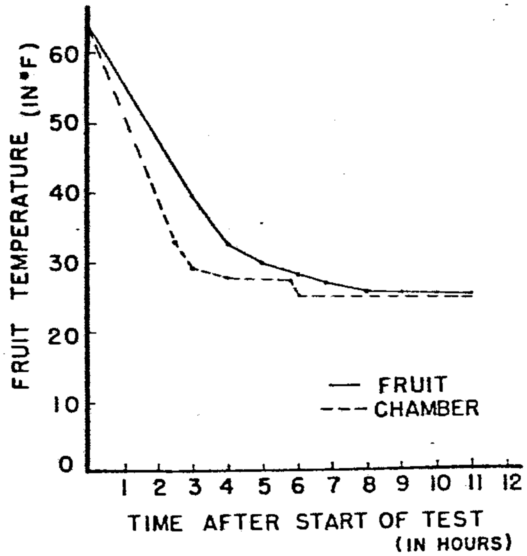

Fig. 2. The average decrease in temperature of Pineapple oranges exposed to a minimum temperature of 26° ± 0.5° F. for 11 hours,

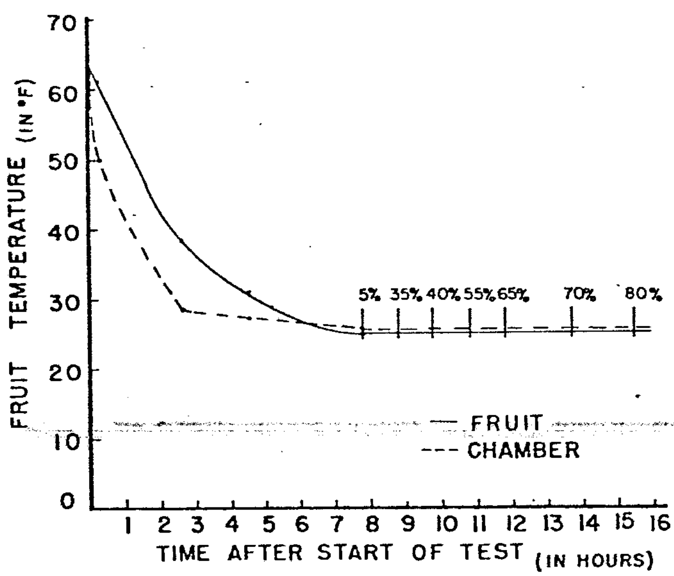

Fig. 3. The average temperature of Pineapple oranges held at 25° ± 0.5° F. for 8.5 hours. The percentage figures appearing above the line represent the per cent fruit frozen at various intervals after the box temperature had been lowered to 25° ± 0.5° F.

Table 1. Time required for orange fruits to freeze when the temperature differential between air and fruit was 3 to 5° F.

Fruit size mm.	Original temp. of fruit °F.	Time before fruit froze hrs.	Minimum temp. before freezing °F.	Maximum temp. after freezing °F.
52	28.5	8.58	26.0	28.5
54	28.5	5.33	26.0	28.0
55	28.5	9.50	26.0	29.0
60	29.0	10.75	26.0	29.0
60	29.5	9.63	26.0	29.0
62	30.0	5.67	26.0	28.0
62	29.0	N.F.[1]	26.0	- -
62	29.5	8.33	26.5	28.0
65	29.5	N.F.	26.0	- -
66	29.5	3.83	26.0	27.5
66	29.5	N.F.	26.0	- -
67	29.0	6.33	26.0	29.0
67	29.5	6.33	26.0	29.0
67	30.5	N.F.	26.0	- -
67	30.0	N.F.	26.5	- -
68	29.0	N.F.	26.0	- -
68	29.0	N.F.	25.5	- -
69	30.0	N.F.	26.0	- -
74	30.0	7.67	25.5	28.0

[1] N.F. = fruit did not freeze.

Florida Citrus Commission and
Florida Citrus Experiment Station,
Lake Alfred, Florida
1048 - 9/19/61 - CHH

Freezing occurred in fruit when its minimum temperature ranged from 24.5-25.5° F. but no freezing occurred at a higher temperature. Fruit size did not appear to affect the rate of temperature decrease nor the minimum temperature obtained by a fruit before freezing.

Effect of a constant 20° F. on freezing of orange fruits. - Orange fruits (varieties Pineapple and Valencia) exposed to 20° ± 0.5° F. for 4 hours subcooled to temperatures as low as 23° F.; however, most fruits subcooled to 24-25° F. before freezing. When any fruit reached its eutectic point and freezing occurred, its temperature increased to within the range of 27.5-28.5° F. and remained at or near this temperature until termination of the test. Generally, fruits froze within 1 hour after air temperature inside the box was 20° F. Therefore, in a 4-hour test fruits were freezing continually for a period of approximately 3 hours, yet no fruits were frozen solid.

Low temperature effect on foliage. - The effect of various exposure temperatures and durations on leaves, limbs and fruit set of Pineapple orange trees are given in Table 2. These data show that a temperature near 20° ± 0.5° F. was the critical temperature for killing mature leaf tissue. Taking 4 hours of exposure as a standard time, it can be noted that less than 1 per cent of the leaves were killed at 23-24° F. Decreasing the temperature to 22° F. increased the per cent leaf kill very little (5 per cent). A further decrease in temperature to 20-21° F. resulted in a definite increase ranging from 50-70 per cent kill, and a temperature of 20° ± 0.5° F. resulted generally in killing all leaves.

Duration of exposure was also involved in the amount of damage to leaf tissue at a given temperature (Table 2). At 22° F. for 4 hours only 5 per cent of the leaves were killed, but an increase to 8.5 hours of exposure at the same temperature resulted in killing 50 per cent of the leaves. It is of interest to note, however, that temperatures of 24° F. or above resulted in no leaf damage even though the exposure time was 10-11 hours.

Leaf drop. - Dead leaves usually fell within 10 days to 2 weeks after freezing except when damage occurred to wood 1 inch or larger in diameter, leaves remained on the trees for periods of more than a month.

Wood damage. - Mature Pineapple trees were fully dormant when exposed to freezing temperatures in January, hence very little wood damage occurred from an exposure to temperatures of 20° ± 0.5° F. for 4 hours.

Mature Valencia trees frozen in February and March were beginning to break dormancy and damage to wood did occur. All Valencia trees were exposed to a temperature of 20° ± 0.5° F. for 4 hours. The amount of wood damage which occurred was generally proportional to the amount of new growth (in inches) at the time of exposure (Table 3). Damage to trees having buds just breaking was confined to the killing of the fine wood around the periphery of the tree. Trees with new growth 4-6 inches long had limbs 4 inches in diameter killed.

Florida Citrus Commission and
Florida Citrus Experiment Station,
Lake Alfred, Florida.
1048 d - 9/19/61 - CHH

Table 2. The effect of freezing temperatures on leaf and wood killing and on subsequent fruit set of Pineapple orange trees

Exposure				
Temperature °F.	Duration hrs.	Leaf kill[1] %	Diameter of wood killed[2] inches	Fruit set[3] %
25-26	11	None	None	100
24-26	10	None	None	100
23-24	4	Less than 1	None	- -[4]
22	4	5	None	100
22	8.5	50	None	60
20-21	4	60-70	None	100
20-21	4.5	50-60	None	100
20-22	6.75	100	0.25	None
20	4	80	None	100
20	4	100	3/16	75
20	4	100	0.5	0
20	4	100	3/16	5
20	4	100	0.5	15

1 Based on observations 2 weeks after tree was frozen.

2 Data taken approximately 3.5 months after freezing.

3 In proportion to percentage of fruit set on unfrozen trees for the same year.

4 This tree was exposed to low temperature a second time.

Table 3. The effect of low temperature exposure on wood damage and fruit set on mature Valencia orange trees exposed to 20° F. for 4 hours

Length of new growth inches	Diameter of wood killed inches	Fruit set %
1/8 - 1/4	3/16 - 1/4	None
1/4 - 1/2	3/8	None
1/2 - 1	1/2 - 1	None
1 - 1 1/2	3/4 - 1	None
2 - 3	1 1/2 - 3	None
3 - 4	1 1/2 - 2	None
4 - 6	2 1/2 - 4	None

Florida Citrus Commission and
Florida Citrus Experiment Station,
Lake Alfred, Florida.
1048 a - 9/19/61 - CHH

<u>Low temperature effect on bloom and fruit set</u>. - Valencia trees frozen in February and March were in a state of active growth as indicated by the presence of varied lengths of new growth. As a result of exposing these trees to 20° F., the fine wood carrying the blossom buds for next year's crop was killed; therefore, none of these trees bloomed and no fruit set occurred (Table 3). Pineapple trees did not exhibit any new growth in January, and therefore, were not as active at the time of freezing. Usually, where wood damage occurred there was little or no crop (Table 2).

Discussion

The cooling rate of Pineapple or Valencia orange fruits was independent of fruit size. Large fruit cooled at about the same rate as small fruit. This is in agreement with observations of Turrell and Perry (1) that thermal conductivity coefficients (k) of citrus fruits should be independent of fruit volume. This apparently holds true within a given fruit, but comparisons between grapefruit, oranges and lemons (1) showed the existence of different "k" values which these authors believed were due to differences in peel thickness between the different kinds of citrus fruits. Apparently the differences in peel thickness encountered between fruits of a given variety are not sufficient to influence the cooling rate of the fruits of that variety.

The freezing point of fruits, or the temperature at which water first crystallizes as ice, was found to range from 27.5-29° F. with the majority of the fruits freezing between 28-29° F. Subcooling was observed to occur in orange fruits, i.e., the temperature of the juice dropped below its freezing point without formation of ice occurring. It was observed that orange fruits subcool as much as 5° F. before freezing under the test conditions used. Characteristically, the temperature of fruits was observed to decrease to approximately 24° F. and remain there for time periods of 15 to 30 minutes even though the air temperature was 20° F. When freezing occurred, the fruit temperature increased to the freezing point of the juice (27.5-29° F.) and remained within 0.5° F. of this temperature for the remainder of a test or until the fruit was frozen solid. This increase in temperature upon freezing and the maintenance of the higher temperature is caused by the release of heat of crystallization.

An exposure of Pineapple orange fruits to an air temperature of 26° F. for 11.25 hours resulted in freezing 58 per cent of the fruits, and an exposure of 25° F. for 8 hours resulted in freezing 80 per cent of the fruits. Temperatures below 24° F. resulted in freezing of all fruits on the tree. It was observed that 24° F. was generally as low as fruit would subcool under conditions of these tests. This does not mean that fruit under field conditions, where heat loss by radiation would occur, would perform in the same manner. It does suggest, however, that some protection of fruits on a low-temperature night could be expected from subcooling.

It appears that a temperature near 20° F. was critical for leaf tissue since very little damage to leaves occurred at higher air temperatures. This

Florida Citrus Commission and
Florida Citrus Experiment Station,
Lake Alfred, Florida.
1048 e - 9/19/61 - CHH

does not imply that under field conditions air temperatures of 20° F. would be necessary before leaf damage occurs, because the loss of heat by radiation under field conditions could not be duplicated in the chamber. It does suggest that if damage to leaf tissue does occur under field conditions, leaf temperature has been at or below 20° F. regardless of the minimum air temperature observed.

Observations on leaf fall following freezing temperatures indicate retention of dead leaves would be a good criteria for estimating severity of wood damage. If dead leaves were retained more than two weeks, it was usually associated with dead wood of one inch or more in diameter. The retention of dead leaves by severely damaged trees might be explained on the basis of an inability of the tree to change the auxin gradiant across the abscission area, hence no abscission layer was formed.

The severity of wood damage at a given temperature was directly associated with the length of new growth at the time of freezing. New growth, of course, is obviously another way of indicating growth activity. Therefore, within certain limits the longer and more abundant the new growth, the more active the cambial area and the greater amount of wood killed by a freezing temperature.

Summary

1. The cooling rate of fruits was independent of fruit size in the two varieties of oranges observed.

2. The freezing point of Pineapple and Valencia orange fruits ranged from 27.5-29° F. with the majority of fruits freezing at 28-29° F.

3. Subcooling as much as 5° F. occurred in orange fruits. Most fruits subcooled to near 24° F. before freezing.

4. Critical temperature for leaf killing was 20° F.

5. Wood damage at freezing temperatures was associated with the length of new growth present. Leaf retention was indicative of wood one inch or greater in diameter killed.

Literature Cited

1. Turrell, F. M., and R. L. Perry. 1957. Specific heat and heat conductivity of citrus fruits. Proc. Amer. Soc. Hort. Sci. 70: 261-265.

2. U. S. Weather Bureau, Fruit-Frost Service. 1957. Calif. Citrog. Nov. 1957: p. 16.

Florida Citrus Commission and
Florida Citrus Experiment Station,
Lake Alfred, Florida.

1048 f - 9/19/61 - CHH