EXPERIMENTAL FORCED-AIR PRECOOLING OF FLORIDA CITRUS FRUIT

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EXPERIMENTAL FORCED-AIR PRECOOLING OF FLORIDA CITRUS FRUIT

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SUMMARY

Citrus fruit in bulk or packed in various types of shipping containers was cooled in a specially designed, pilot-scale experimental precooler and the cooling rate was studied. The precooler forced air through the void spaces of the fruit. Principal variables affecting cooling rate were load size, initial fruit temperature, and rate of airflow. Because of the precooler's limited refrigeration, air temperatures surged to a peak, usually to about 40° F., in the first 5 minutes of the test, then declined at about the same rate as that of the cooling fruit. This peak and decline pattern proved beneficial to fruit physiology. A similar pattern in a commercial system would be more economical than in the experimental precooler where the air temperature was held at the same level throughout the cooling period. The final air temperature varied from 20° to 35° depending on the fruit load and other test conditions contributing to the total heat load on the refrigeration system. In tests in which the final air temperature was 20°, fruit exhibited no physiological breakdown or subsequent increased decay.

The mass-average temperature of oranges, tangerines, and tangelos was reduced 35° F. in an hour or less. Grapefruit cooled more slowly. After approximately 15 minutes, slightly more for grapefruit, temperature distribution within the fruit followed an approximate mathematically predictable pattern for homogeneous spheres.

Oranges packed in 4/5-bushel wirebound boxes or in ventilated 4/5-bushel fiberboard cartons, or loose oranges in 8-pound perforated polyethylene bags cooled more slowly than bulk fruit. Fruit in polyethylene bags packed in nonventilated bagmaster cartons cooled very slowly.

Air at a temperature below the freezing point of the fruit, as used in this method, improves cooling. However, the slight difference between freezing point and minimum temperature demands careful adjustment of cooling time to rate of airflow and air temperature. Findings, therefore, emphasize the rate of airflow needed to produce optimum cooling and maximum system efficiency.

Generally, system performance was inversely proportional to rate of airflow. An approach velocity of approximately 300 feet per minute was optimum for the various conditions studied.

Weight loss, presumably moisture vaporized from fruit during the tests, averaged less than 1 percent. Humidity control was not attempted.

To determine the commercial potential of this forced-air precooling technique, we evaluated the principal variables in terms of a performance index and cost per pound. These were combined to introduce a new criterion of overall performance-cost index of performance. The cost index of performance for the experimental precooler was higher than would be expected for a similarly designed commercial system. Findings show that the method does have commercial feasibility.

REASON FOR RESEARCH

In a normal year, approximately 35 million hundredweight of fresh citrus fruits, including oranges, grapefruit, tangerines, and specialty types, are shipped from Florida. At average prices, this represents a gross income of $140 million to the fresh citrus industry. To maintain this market against increased pressure from processed citrus and synthetic products, growers must ship high-quality fruit that has been conditioned to withstand several days (sometimes weeks) of transportation and warehousing as well as an extended shelf life after purchase by consumers.

In 1955, Pentzer (23)[2] estimated that one-fifth of the Nation's perishable produce is never consumed, because of waste and spoilage. He further suggested that much of the remainder was inferior in quality and less nutritious because of poor handling practices. In citrus fruits, this waste can be conservatively estimated to average 10 percent of all fresh fruit shipped annually. Some of these losses are caused by abuse, but most result from deterioration.

Adequate and prompt refrigeration of citrus before shipment, and continued refrigeration until use, will

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[2] Underscored numbers in parentheses refer to Literature Cited p. 19.

sharply curtail losses from decay and other forms of deterioration.

Precooling (cooling before shipment) is widely accepted among packers of perishable produce. To be most effective, precooling must quickly and completely extract a predetermined quantity of heat from the produce. Hydrocooling satisfies this requirement.

Following the example of the peach industry and certain vegetable producers, some packers of fresh citrus fruits used hydrocooling for rapid precooling at the packing plant. It soon became apparent, however, that a fungicide in the cooling water was essential to hold decay to tolerable levels. Also, fruit cooled with water seemed more susceptible to decay upon warming. Certain types of citrus, notably grapefruit, exhibited subsequent chilling injury. These undesirable features of citrus hydrocooling—as well as the need for a precooling system that could be integrated into the packing line—have rekindled an interest in forced-air precooling systems.

More than half of the citrus fruit shipped from Florida in recent years has been packaged in small containers, such as 4/5-bushel wirebound boxes, 4/5-bushel fiberboard cartons, mesh bags, polyethylene bags, and bagmaster cartons (4). Citrus fruit that has not been precooled before packaging succumbs rapidly to decay and other deterioration when subjected to the poorly ventilated conditions that exist in most small shipping containers.

Objectives

This research was undertaken to explore engineering problems of forced-air precooling of oranges, grapefruit, tangerines, and tangelos and its biological effects on the fruit. The general objective was to determine the commercial potential of cooling the fruit by forcing air at temperatures substantially below the fruit's freezing point through the void spaces in bulk lots of fruit. Specifically, the work was aimed at optimizing the rate of airflow and air temperature for maximum efficiency and effectiveness in forced-air precooling.

Two less significant objectives were to compare cooling of place-packed citrus with that in random-filled bulk boxes and cooling rates of citrus in different types of shipping containers.

Literature Review

Precooling of citrus fruit was first recommended by Powell (25) in 1908. Ramsey (26), in 1915, emphasized that precooling was valuable in insuring sound fruit on arrival at the terminal markets. He suggested that, regardless of precooling method used, fruit should be precooled as promptly and as thoroughly as possible after harvest. These early recommendations led to construction of "precooling rooms" in a few Florida packinghouses. However, most "precooling" was accomplished in refrigerator cars.

From 1920 to 1950, very little progress was made toward adoption of precooling of Florida citrus. Successful research on hydrocooling peaches and the peach industry's subsequent adoption of hydrocooling, as summarized by Haller (14) in 1952, renewed interest in precooling Florida citrus fruit. Leggett and Sutton (22) conducted the first known laboratory-scale experiment on precooling Florida citrus fruit. Oranges and grapefruit were cooled more rapidly with cold water and cold air at high velocity than in a conventional air precooling room.

Preliminary investigations, reviewed by Grierson (5) in 1957, indicated the possibility of hydrocooling oranges before packing. However, Harvey and others (15) reported injury in transit and Eaks (3) observed physiological shock in hydrocooled California oranges. Interest in hydrocooling centered around oranges, since grapefruit not only cooled more slowly but also showed chilling injury. Grierson and Hayward (7) reported that hydrocooling produced excessive rates of decay unless 0.1 percent sodium-o-phenylphenate was added to the cooling water. Peel injury, particularly of Pineapple oranges, was increased. Hydrocooled grapefruit exhibited severe peel injury, increased decay, and loss of gloss. Grierson (6), in his instructions on "Dowicooling," recommended that the pH of the cooling water be adjusted from 10.5 to 12.0 to avoid excessive residue deposits.

In simulated transit experiments with oranges in polyethylene bags packed in bagmaster cartons, Grierson, Hayward, and Oberbacher (11) found that "Dowicooling" gave excellent decay control, provided the fruit was subsequently held at 50° F.; a week at 70° F. produced a sharp increase in decay. By contrast, oranges treated with sodium-o-phenylphenate solution—Hopkins and Loucks (20)—and air-cooled rapidly, showed no signs of flareup in decay. Grierson and Hayward (8) reported that continuous refrigeration after hydrocooling or Dowicooling was essential to maintain quality of oranges in polyethylene bags, along with sodium-o-phenylphenate (31) and diphenyl (32) as decay controls. Hayward and Oberbacher (18) found that continuous refrigeration at 50° F. greatly reduced decay and increased effectiveness of fungicides and precooling. Hayward, Oberbacher, and Grierson (19) reported that decay of Hamlin and Pineapple oranges packed in polyethylene bags in bagmaster cartons decreased as the number of holes in the bags increased. Hayward (16) and Hayward and Long (17) mentioned that hydrocooling might extend the shelf life of Valencia oranges but appeared to damage grapefruit and tangerines and thus increase subsequent decay.

Difficulties with hydrocooling ("Dowicooling") led to investigation of methods of cooling fruits before or after packing them in fiberboard cartons or in polyethylene bags and slightly modified bagmaster cartons. Grierson and Hayward (9, 10) improved air cooling of oranges in polyethylene bags by using bagmaster cartons with slotted tops and bottoms instead of side vents. The cartons were stacked tightly in a slotted-floor cold room, and a slight pressure differential was maintained across the stacks. Oranges treated with sodium-o-phenylphenate solution and air precooled had less decay than "Dowicooled" fruit. As found previously, continuous refrigeration and a sufficient number of ventilation holes were necessary to minimize decay of fruit in polyethylene bags.

According to Guillou (12), investigations of forced-air precooling in California led to the development of commercial forced-aid precooling installations as described by Smith and Perry (28). These installations employed principles of both forced-air precooling and room cooling but did not use air below 32° F. Advantages cited by Guillou (12) are as follows:

- A pressure differential across the stack of packed containers draws air through, rather than around, the containers.
- Airflow is countercurrent, so that fan energy is utilized more efficiently.
- More produce can be handled since cooling is more rapid than conventional room precooling.
- Fruit is not wetted.

Among the disadvantages cited by Guillou were (1) extra handling, (2) necessity for venting containers to permit entry of cold air, (3) increasingly uneven cooling as air passed through several tiers of containers, and (4) impracticability of achieving cooling rates comparable to those of hydrocooling or vacuum cooling.

Aside from the work of Leggett and Sutton (22) and Grierson and Hayward (9, 10), there has been no previous study of forced-air precooling of citrus in Florida. When the present research was begun, no commercial units, based on California designs, had been built or were under construction.

DESIGN OF PRECOOLER AND EXPERIMENTS

The pilot-plant precooler (fig. 1) was constructed on the rear platform of the Citrus Laboratory, Department of Fruit Crops, University of Florida. Research was carried out over two seasons.

The first season was devoted to checking equipment, installing and calibrating instruments, surveying airflow patterns, and measuring rates of airflow. Also, 144 preliminary test runs were conducted under various

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Figure 1.—Pilot-plant forced-air precooler shown on rear platform of the Citrus Laboratory, Department of Fruit Crops, University of Florida.

conditions, and modifications were made to improve precooler performance.

Since there was no background on this type of forced-air precooling of citrus fruits in Florida, it was necessary to combine flexibility with practicality in the design of the pilot-plant precooler. Broad preliminary tests established operating limits for fastest rates of cooling without immediate or subsequent injury to fruit.

Results of the preliminary tests made possible the development of techniques used in 114 test runs during the second season.

Materials and Equipment

The test unit (fig. 2) was constructed of 1/2-inch marine plywood sheathing nailed to a framework of 2- by 4-inch wooden planks. Dimensions were 10 feet long by 10 feet wide by 8 feet high. The floor, sidewalls, and top were insulated with 3 inches of polystyrene with inner and outer wraps of polyethylene vapor seal. The product cooling chamber was originally designed to accommodate two standard 42-inch-square, 1/2-ton-capacity pallet boxes, stacked one upon the other. Later, the lower box was made into a plenum chamber to improve system efficiency.

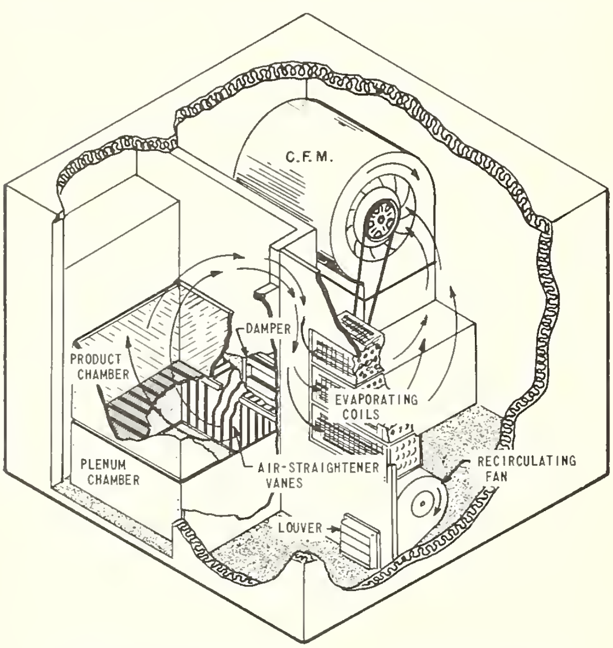


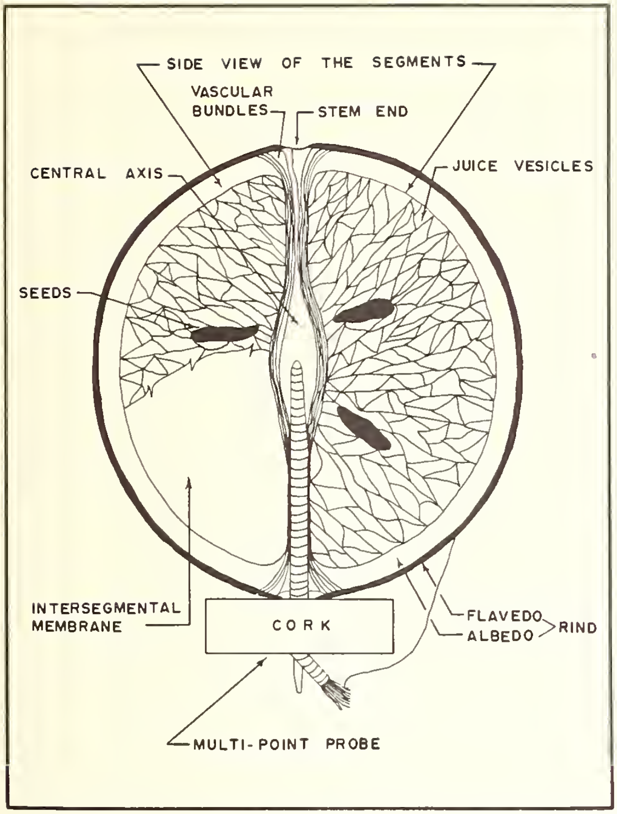
Figure 2.—Cutaway of experimental forced-air precooler, showing equipment arrangement and airflow pattern.

Cooling air was circulated by a backward-blade centrifugal fan with a rated delivery (standard temperature and pressure) of 11,500 cubic feet per minute (c.f.m.), against a static pressure of 3 inches of water. Fan performance was calibrated at 1,400 revolutions per minute (r.p.m.), but preliminary tests demonstrated that substantially reduced fan speeds also cooled effectively. Variation of fan speed by interchangeable pulleys permitted regulation of airflow over a wide range. Airflow could be further regulated by a damper between the fan discharge and the air plenum.

Three condensing units, each with a maximum rated capacity of 1 1/2 tons of refrigeration, supplied compressed refrigerant to a bank of four-row-deep evaporator coils with a face area of 6.96 square feet. A 2,000-watt electric heater in the throat of the fan outlet helped regulate air temperature.

In all except 40 runs, temperature at the center and surface of the fruit was measured with 30 American wire gage (a.w.g.) copper-constantan thermocouples. In runs 194 through 233, 30 a.w.g. copper-constantan multipoint thermocouple probes connected to 24 a.w.g. copper-constantan extension wire (fig. 3) were used. Air temperature was measured with 24 a.w.g. copper-constantan thermocouples. All of the thermocouples were connected to 24 a.w.g. copper-constantan extension wires. Temperature was recorded by strip chart multipoint potentiometers. A vertical manometer graduated in 0.1-inch units, with a range from 0 to 6 inches of water measured the static pressure drop across the fan. Electric energy input was measured by industrial watt-hour meters.

Two types of pallet boxes were tested. One, a standard wooden box (W), measured 42 by 42 by 26 inches inside (fig. 4) and weighed 120 pounds. Openings in the bottom of the box were 6.5 percent of the total area. The other, a specially made expanded metal mesh pallet box (M) with angle iron frame, measured 42 by 42 by 30 inches inside (fig. 5) and weighed 160 pounds. Openings in the bottom of the box were 69.0 percent of total area. Plywood fastened to sides of the box prevented escape of air through sides. Capacity of both boxes loaded to a depth of 26 inches was about 1,000 pounds.



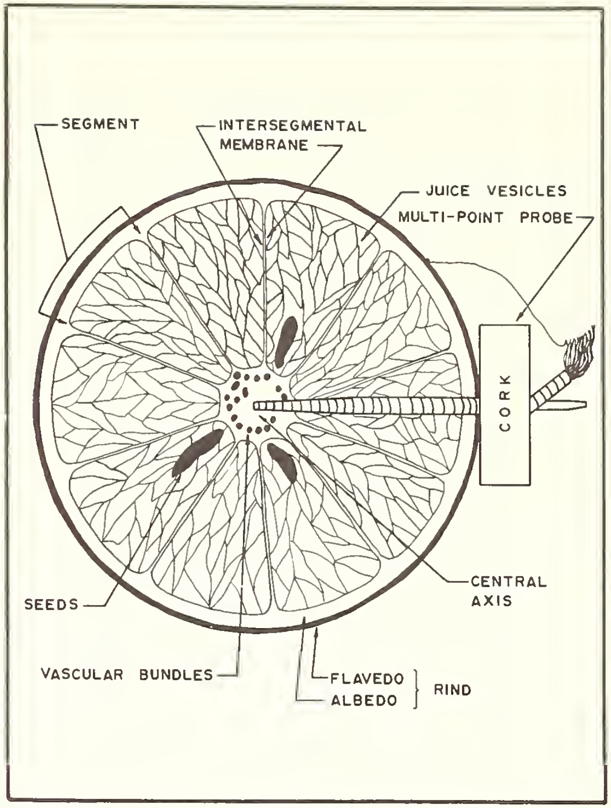


Figure 3.—Cross-section of citrus fruit showing thermal probe inserted (left) through vascular bundles in polar plane and (right) through juice vesicles in equatorial plane.

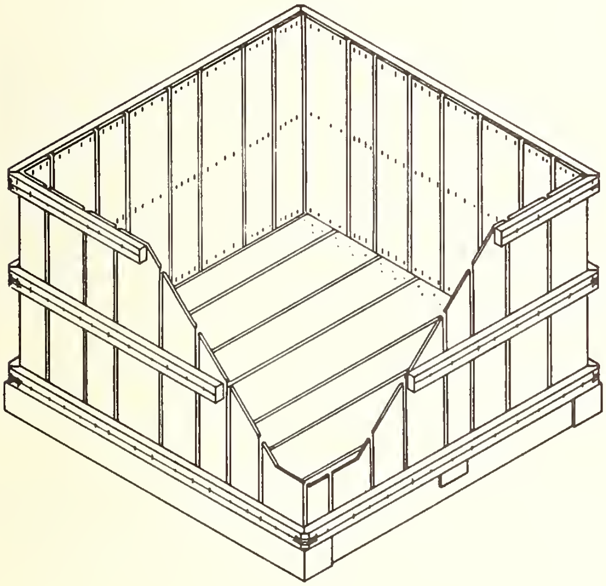


Figure 4.—Design of standard wooden pallet box used in forced-air precooling tests.

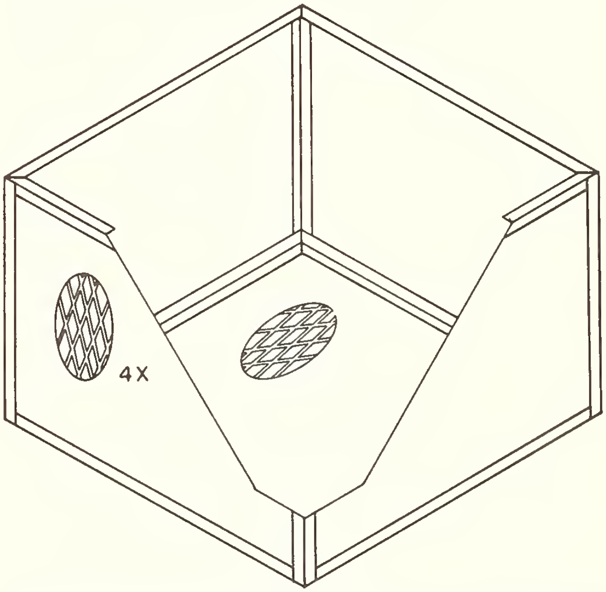


Figure 5.—Metal box constructed of 1/8-inch-thick expanded black iron. Sides were sealed with plywood for tests; bottom was not sealed. Ovals show design of the mesh.

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Sources of Fruit

Fruit came from two sources: (1) The Department of Fruit Crops, University of Florida, Gainesville, Fla., supplied Hamlin, Pineapple, and Valencia oranges, Duncan grapefruit, and Dancy tangerines from its groves. Fruit was picked tree-run, washed, and waxed; none was degreened. (2) The Citrus Experiment Station supplied fruit from CES groves treated with sodium-o-phenylphenate to retard decay. Throughout the first season, fruit from the Citrus Experiment Station was procured every 3 to 4 weeks and stored at 40° F. until tested.

Before the tests of the second season were completed, a severe freeze destroyed most of the Florida citrus fruit. The remaining bulk tests, therefore, used fruit harvested at the Department of Fruit Crops' groves before the freeze. Tests in shipping containers were completed with Valencia oranges from commercial packinghouses; these oranges showed moderate internal freeze damage.

PRELIMINARY INVESTIGATIONS

Experimental Procedure

Fruits used in the tests were Hamlin, Pineapple, and Valencia oranges, Duncan grapefruit, and Dancy tangerines. Type of bulk box, load size, rate of airflow and air distribution, and initial fruit temperature were evaluated for each type of fruit. Emphasized were effects on cooling rate of load size, mass rate of airflow, and pattern of airflow through the fruit. In addition, methods of handling the large quantities of fruit between test runs were constantly improved.

Each test run followed a procedure developed during the first series of experiments with Hamlin and Pineapple oranges. Fruit was warmed before each test. Initially, fruit was unloaded and reweighed between test runs. However, because loss in weight was so low and loading and unloading fruit by hand so tedious, fruit was reweighed only when size of load, type of pallet box, or fruit variety was changed. Fruit in bulk lots was tree run. Fruit to be measured for temperature was selected according to representative size, uniformity, and freedom from blemishes.

Internal fruit temperature within the load was sensed by inserting thermocouples through the blossom ends to the centers of several fruit and placing the fruit at strategic locations within the pile. Surface temperature was sensed on the same fruit by securely fastening one thermocouple to the rind. Data from all locations were averaged for compilation and analysis.

Original plans were to begin precooling at an initial uniform fruit temperature of 85° F. It soon became obvious, however, that warming a load of fruit from 40° to 85° would take several hours. Therefore, the required initial fruit temperature was reduced to 70°. This temperature was used throughout, except when initial fruit temperature was a treatment variable.

Original plans were to test a combination of airflow rates and constant air temperature intervals ranging from 15° to 30° F. Early tests demonstrated that, because of the heavy initial cooling load, refrigeration capacity could not maintain a constant air temperature. Instead, within a few minutes the temperature surged to a peak—the peak's magnitude depending on the test—then steadily declined at a rate corresponding to that of the cooling fruit. When the precooler was not loaded, the temperature could be reduced as low as 0°.

In early tests, fruit exposed to an initial air blast at 5° F. showed no sign of subsequent injury to rind or pulp. A "starting" temperature of 15° was selected as optimum. This temperature required a "temperature pull-down" time of about one-half hour. Lower temperatures required longer pull-down times and increased frosting of the coil.

Arrangement of the components of the forced-air precooler made it necessary to lower the temperature while the fruit was in the cooling chamber. The cooling chamber was partially closed off from the rest of the precooler by closing the damper during temperature pull-down. But some cold air always leaked around the damper and escaped through the warm air return. This leakage reduced air temperature around fruit in the load and made it difficult to control initial fruit temperatures.

Precooling was begun by turning on the fan and opening the damper to a predetermined setting. In the first nine series of test runs cooling was continued until the center temperature of oranges and tangerines reached 40° F, and grapefruit 50°. Subsequent tests were run for a definite period, usually 1 1/2 hours. Static pressure and power delivered to the fan motor and refrigeration units were recorded at the beginning and near the end of each test. Upon conclusion of a test, the fruit was rewarmed for the next test.

Results and Discussion of Preliminary Investigations

Of the 144 preliminary test runs, six were selected as a representative cross section of principal test treatments including fruit type, initial fruit temperature, and mass rate of airflow. Designated as A through F in table 1, they are listed with temperature response and power requirements.

The precooler was substantially altered because refrigeration and handling of fruit was inefficient.

Improper system design and operating practices raised the values of logarithmic mean air temperature and energy requirements for the fan motor and condensing units to undesirable levels. For example, in test run E, reducing the airflow rate to about one-half that of test run D improved cooling. The comparison of test runs D and E further illustrates that regulating airflow with the damper, rather than fan speed, did not appreciably reduce fan power requirements.

In the original design, auxiliary fans circulated air over the coils while the main fan circulated air over the fruit. This method was inefficient because much of the air circulated through the fruit without being exposed to the cooling coils. Relocation of the cooling coils, as shown in figure 2, forced all the air through the coils and improved efficiency for the main investigations.

The relation between air temperature and the temperatures at the center and surface of the fruit, listed by test run in table 1, is illustrated graphically in figures 6 and 7.

The cooling rate shown in these charts is indicative of commercial potential.

Air distribution within the lot and its movement to and from the bulk lot did not significantly affect the cooling rate of the fruit. Thus, the air pattern illustrated in figure 2 was used, both in the final preliminary test runs listed in table 1 and in all the main test runs to be discussed later. This pattern was selected primarily because it made getting fruit into and out of the precooler easier. The lower bulk box was converted into a plenum that supported the box containing the fruit, and the whole assembly was rolled into and out of the precooler with relative ease.

Repeated warming and cooling of the fruit under test

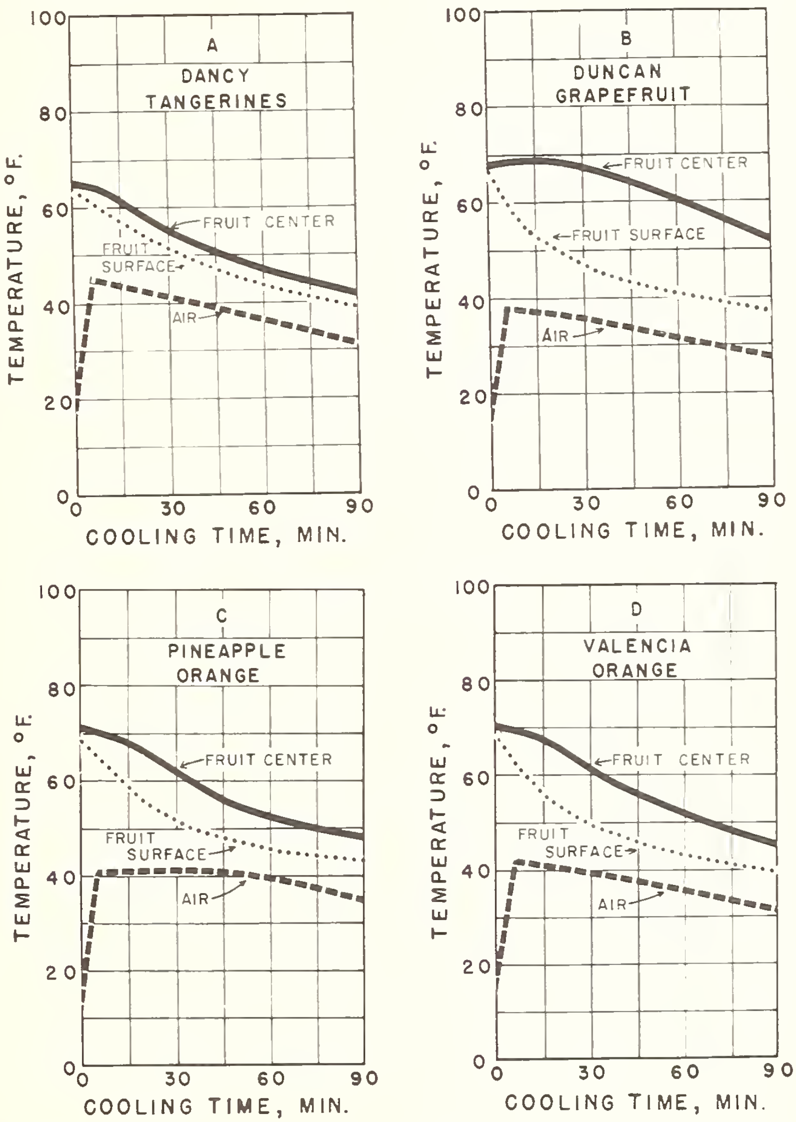

Figure 6.—Effect of fruit type and size on fruit temperature response for test runs A, B, C, and D (see table 1 for listings).

during the first season produced no additional decay or physiological breakdown beyond that reasonably expected during or following short storage periods. Decay and breakdown were slight among fruit subjected to as many as 24 cooling and rewarming cycles within 1 to 2 weeks after harvest. Moderate increases were noted 3 to 4 weeks after harvest. No peel injury was observed. These fruit were repeatedly exposed to air at temperatures substantially below 32° F. However, as described in the previous section, fruit was not subjected to air below the freezing point of fruit during the entire cooling period.

The early peak and subsequent decline of air temperature corresponding with cooling of fruit may be the cause for the low incidence of physiological breakdown and other observable injury. This condition allows the fruit to cool internally at a rate proportional to its surface temperature and thereby prevents severe temperature gradients that could induce stress in the tissue.

Loss of weight, presumably moisture, was low, from 0.5 to 1.0 percent, in all test runs. Fruit held in 40° F. storage following precooling remained firm and unshriveled for 4 weeks after harvest.

TABLE 1.—*Test treatments, temperature response, and operating data for selected precooling test runs of citrus fruit*[1]

Test run	Fruit and variety	Average diameter	Load	Temperature			Mass rate of airflow[3]		Energy used	
				Initial fruit	Log mean air[2]	Final fruit (center)	Per hr. per sq. ft.	Per hr. per lb.	Fan motor	Condensing units
		In.	*Lb.*	*° F.*	*° F.*	*° F.*	*1,000 lb.*	*1,000 lb.*	*Kw.-hr.*	*Kw.-hr.*
A	Tangerines, Dancy	2.16	1,000	67	43.5	42	18.6	48.36	7.07	8.76
B	Grapefruit, Duncan	4.25	512	69	41.1	53	18.7	94.90	7.16	9.49
C	Oranges, Pineapple	2.80	502	71	43.2	48	17.6	91.40	6.92	10.14
D	Oranges, Valencia	2.95	500	71	42.7	46	18.5	96.5	7.02	10.11
E	Oranges, Valencia	2.88	500	75	39.9	43	9.5	49.5	6.09	8.86
F	Oranges, Valencia	2.88	500	95	48.1	50	9.3	48.6	6.05	8.82

[1] Tests conducted in standard wooden pallet box using the air pattern illustrated in figure 2. Cooling time—1.5 hours.
[2] Calculated by procedure given in Appendix B, Logarithmic Mean Air Temperature.
[3] Regulated by damper setting with fan at 1,400 r.p.m. Minimum free flow area—2.6 square feet.

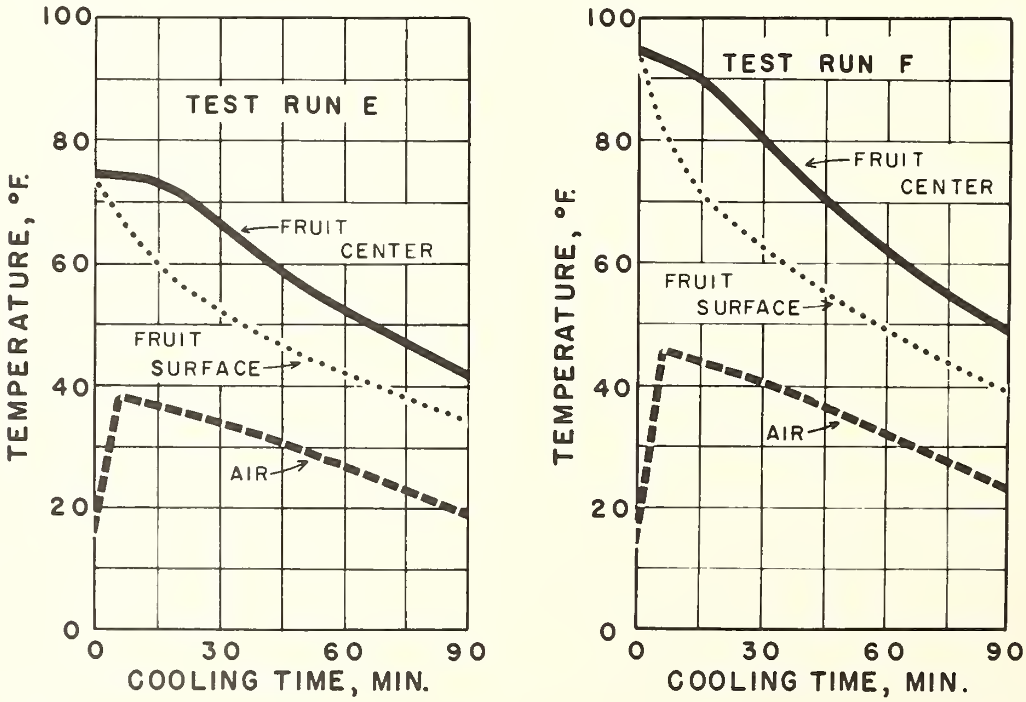

Figure 7.—Effect of initial fruit temperature on fruit temperature response for test runs E and F (see table 1 for listings).

MAIN INVESTIGATIONS

Experimental Procedures

During the second season, 114 test runs, numbers 145 through 258, were conducted. With the exception of a few tests comparing place packing with random filling in pallet boxes and pallet boxes with small containers, treatments and procedures were the same as those in the preliminary investigations.

Fruit was sorted into commercial sizes and weighed before being loaded into the test box. It was reweighed after each series of tests.

The same fruit was precooled repeatedly and replaced only to bring a load up to desired weight or to eliminate decayed fruit.

Fruit temperature

Fruits selected for temperature measurement were strategically placed throughout the pile in several locations. The recorded data from these locations were averaged to obtain a single value for temperature at the specified point within or on the surface of the fruit.

An objective of test runs 194 through 233 was to ascertain how temperature was distributed inside citrus fruits during precooling and to locate the point of mass-average temperature (defined on p. 15). Hamlin oranges, a mixture of half Marsh and half Foster grapefruit, and Orlando tangelos were used. Dancy tangerines and other varieties of oranges and grapefruit could not be included because unfrozen fruit were scarce in Florida during these experiments.

Test runs followed the procedure previously described, except in sensing fruit temperature. Three pairs of multipoint thermal probes, measuring 2.00, 1.50, and 1.3125 inches, were inserted into selected fruit. The length of the probes corresponded to the average radii of size 80 grapefruit, size 200 oranges, and size 250 oranges, respectively. Insulated junctions of 30 a.w.g. nylon-covered copper-constantan thermocouples were at the tip and at intervals of 0.25 inch along each probe. A separate thermocouple, also 30 a.w.g., sensed surface temperature.

Six fruit, carefully selected for uniformity of size, weight, and freedom from blemishes, were placed in a load. Three fruit were placed at 6 inches and three at 12 inches from the bottom of the pallet box.

All probes were inserted through the blossom end, or polar direction (fig. 3, left) in test runs 194 to 196. In subsequent test runs, probes in the three fruit at the 12-inch level were in the equatorial direction (fig. 3, right). Temperature was sensed from 44 data points: 16 at intervals of 7.5 minutes and 28 at intervals of 15.0 minutes.

Multipoint thermal probes were sensing devices in two test runs (234 and 235) of Hamlin oranges packed in 4/5-bushel wirebound boxes. Fruit with a probe or probes was placed at the center of a packed box, which was placed among other boxes in a two-tier stacking pattern.

Energy consumption for 1 hour of precooling varied from 1 to 7.34 kilowatt-hours for the fan and from 4.75 to 9.87 kilowatt-hours for the refrigeration units. Operating cost per hundredweight varied from $0.23 to $0.084.

Air temperature and distribution

Averaging the temperature of air entering and leaving the product chamber at the particular points in time yielded values of air temperature. An average value was taken as the representative temperature of air surrounding the fruit within the load.

Heat transfer parameters are usually evaluated by measuring the internal fruit temperature response against surrounding fluid temperature. If fluid temperature is constant, temperature response, expressed as a temperature ratio is sufficient for evaluation. When, however, as in these tests, fluid temperature is not constant, it becomes desirable to use a standard reference point for the fluid. In the analysis of these tests the final air temperature at the end of a test run was the reference point for computing fruit temperature distribution equations (Appendix B); log mean air temperature was used for computing surface heat transfer coefficient; and the log mean temperature difference between air and fruit was used to compute cooling coefficients.

Rate of airflow

Airflow at nearly continuous rates was studied for effect on fruit quality. Tests were based on results of preliminary investigations and on Holmes' study of the relation of airflow to resistance through citrus fruit in bulk (fig. 8).[3] Manipulation of fan speed and damper setting varied rate of flow. Three fan speeds and four damper settings were employed. Although fan speed and damper setting primarily governed the airflow rate, box bottom, load size, and fruit type exerted some influence. The effect of these variables on rate of airflow is shown in table 8, Appendix C.

To measure air velocity we took 63 traverse readings with a vane anemometer across the face of the evaporator coils. The average of these readings was converted to volume and mass rate of flow as described in Appendix B. These measurements were checked

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[3] Holmes, E. S. Unpublished data. Progress report for project No. 1111. Agr. Expt. Sta., Univ. Fla. 1961-62.

Holmes' findings are listed in table 7. Appendix C. These data were plotted on semilogarithmic coordinates as shown in figure 8.

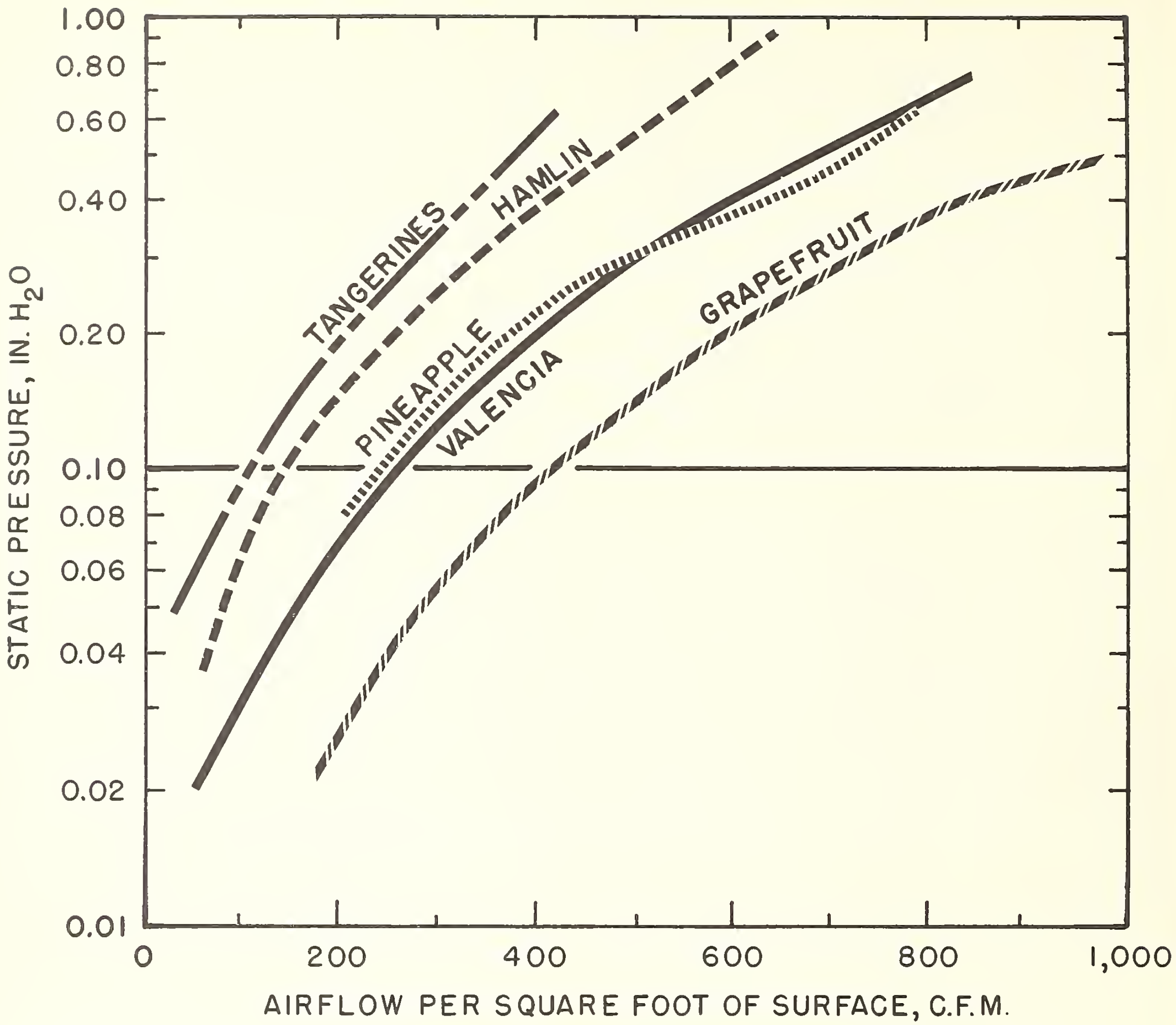

Figure 8—Relation between airflow and resistance through fruit.

against the manufacturer's fan performance data at the static pressure drop across the fan observed for the corresponding fan speed.

Analysis of Results

Temperature distribution

Data from forced-air precooling test runs of Hamlin oranges, Marsh and Foster grapefruit, and Orlando tangelos, 194 to 233, were analyzed according to the procedure outlined by Smith and Bennett (29) for estimating mass-average temperature of hydrocooled peaches. The average point of mass-average temperature was found to be 0.784R, 0.772R, and 0.795R for oranges, grapefruit, and tangelos, respectively.

Fruit temperature, as unaccomplished temperature change, was correlated with values of time and ratio of the distance from fruit center to surface. Average air temperature adjacent to fruit in the product chamber at the end of each test run was used in computing the temperature ratio. Coefficients were obtained for 248 multiple regression equations—one for each of six probes in 40 test runs and for each of four probes in two test runs—in the form of a third-degree polynomial. Individual equations were examined; then the original data of test runs 194 to 233 were combined and reanalyzed in 12 groups as listed in table 2. Model equations and general analytical procedure are given in Appendix B for temperature distribution and location of the mass- average point, respectively.

Total correlation and regression coefficients of 12 fruit temperature distribution equations for grouped

TABLE 2.—*Groupings of test runs for fruit temperature distribution equations*[1]

Test group No.	Fruit and variety	Designated test run numbers
1	Hamlin oranges	200-205
2	do.	224-226, 229-231
3	do.	200-205,224-226, 229-231
4	do.	227, 228, 232, 233
5	do.	200-205[2]
6	do.	200-205[3]
7	Marsh and Foster grapefruit	194-199
8	do.	218-223
9	do.	194-199, 218-223
10	Orlando tangelos	206-211
11	do.	212-217
12	do.	206-217

[1] See table 8, Appendix C, for treatments.
[2] Polar probe insertion was used in these test runs.
[3] Equatorial probe insertion was used.

data of test runs 194 to 233 are presented in table 3. The high correlation coefficients are characteristic of the data. Expressing temperature response and distance along the radius as ratios reduces variations to a normalized value, thus permitting a good fit of the computed equation to the experimental data points. Total correlation coefficients that are noticeably lower than normal, as in test groups 2 and 4, probably result from combining noncongruent test runs. Much of these lower than normal coefficients are possibly attributable to rate of airflow. The polynomial coefficient, b_1, in test group 4, which consisted of test runs with 1,000-pound loads, indicates a slower temperature response than the others in the group of Hamlin oranges. Treatments listed in table 8 indicate that a reduced rate of airflow and an increased load slowed temperature response.

Temperature response curves (figs. 9 and 10) were plotted from the selected prediction equations whose polynomial coefficients are listed in table 3. The equations were solved at time increments of one-quarter hour and at radius ratio values of 0 for the center, 0.5 for half the radius, 0.7937 for the mass center (point on the radius that divides the mass), and 1.0 for the surface. The resulting temperature ratios were converted to whole values as described in Appendix B.

Effect of rate of air movement on Hamlin oranges, Marsh and Foster grapefruit, and Orlando tangelos is illustrated in figure 9. The reduced airflow, obtained at a fan speed of 670 r.p.m., and the 500-pound test load combined produced the fastest temperature response at the surface and at the fruit mass center. This phenomenon is characteristic of the system and may be explained as follows: As cooling progressed, the refrigeration system was able to reduce the air temperature more rapidly at the lower airflow rate and a corresponding decrease in fruit temperature at or near the surface resulted. The delayed response noted at the center of Hamlin oranges and Marsh and Foster grapefruit is characteristic of the lag factor of the fruit in relation to surface heat transfer, as described by Pflug and Blaisdell (24).

The relation of surface temperature to cooling time is a valuable guide in establishing operating criteria. For example, results revealed that temperature on the immediate surface may be reduced to as low as 25° F.

TABLE 3.—*Total correlation and regression coefficients of fruit temperature distribution equations for grouped data of orange, grapefruit, and tangelo test runs*

Test group No[1]	Total correlation coefficients	Polynomial coefficients							
		a	b_1	b_2	b_3	b_4	b_5	b_6	b_7
1	0.97676	1.08614	-.84871	-.26619	0.19574	0.08217	-.01792	-.22864	0.13002
2	.90438	1.09012	-.85558	-.27064	.25196	.27865	-.07396	-.37425	-.00284
3	.96225	1.09859	-.86477	-.27967	.16479	.15175	.01143	-.28038	.10921
4	.90534	1.07102	-.53944	-.24103	-.02568	.21340	.04572	-.24153	.00546
5	.98160	1.10142	-.89605	-.36204	.20512	.28922	-.01374	-.37535	.16349
6	.97951	1.07248	-.80625	-.18221	.19448	-.09808	-.02542	-.09725	.09529
7	.93915	1.06025	-.64636	.09432	.15730	-.71279	-.03534	.17869	.07600
8	.93963	1.07323	-.45046	-.30656	.05485	.57948	-.01964	-.69874	-.17430
9	.93454	1.05483	-.58131	.18190	.04592	-.81327	.01495	.20218	.04745
10	.96611	1.07616	-.81758	-.30390	.13091	.25515	.01667	-.31811	.18806
11	.96462	1.09830	-.77592	-.35561	.10876	.45960	.01233	-.47870	.09456
12	.96157	1.03687	-.79585	-.33033	.11884	.36297	.01197	-.40227	.10563

[1] See table 2 and table 8, Appendix C, for individual test run treatments.

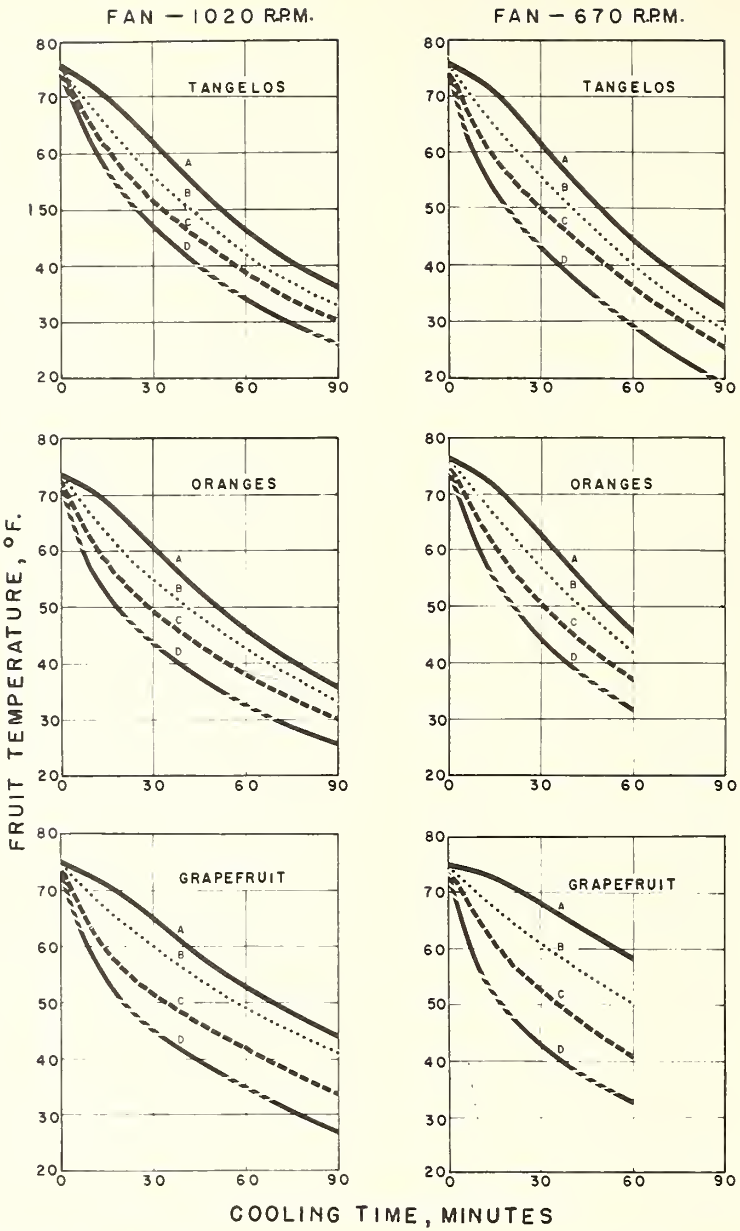

Figure 9.—Predicted internal fruit temperature distribution during forced-air precooling of 500-pound bulk lots of Orlando tangelos, Hamlin oranges, and Marsh and Foster grapefruit. Temperature response shown at (A) fruit center, (B) half-radius, (C) theoretical mass-average, (D) surface.

for a brief period of time without injury to the fruit. However, at this temperature, there is danger of freezing injury. Therefore, in practice, surface temperature should never be allowed to go below about 28° F.

The temperature distribution of a test group of Hamlin oranges at five specified times during cooling is shown in figure 11. Data for these curves were generated by use of equation IV in Appendix B.

The 1,000-pound test loads of Hamlin oranges cooled more slowly than the 500-pound loads; yet after 1 hour of cooling, predicted center temperature in the lighter load was only 5° F. less than in the heavier load.

Figure 10 and the polynomial coefficients b_1 and b_2 in table 3 indicate that direction of probe affected accuracy of temperature measurement. The inaccuracy probably resulted from conduction error along the polar probe and perhaps some slight irregularity of heat flow around and through the vascular bundles. Because of its

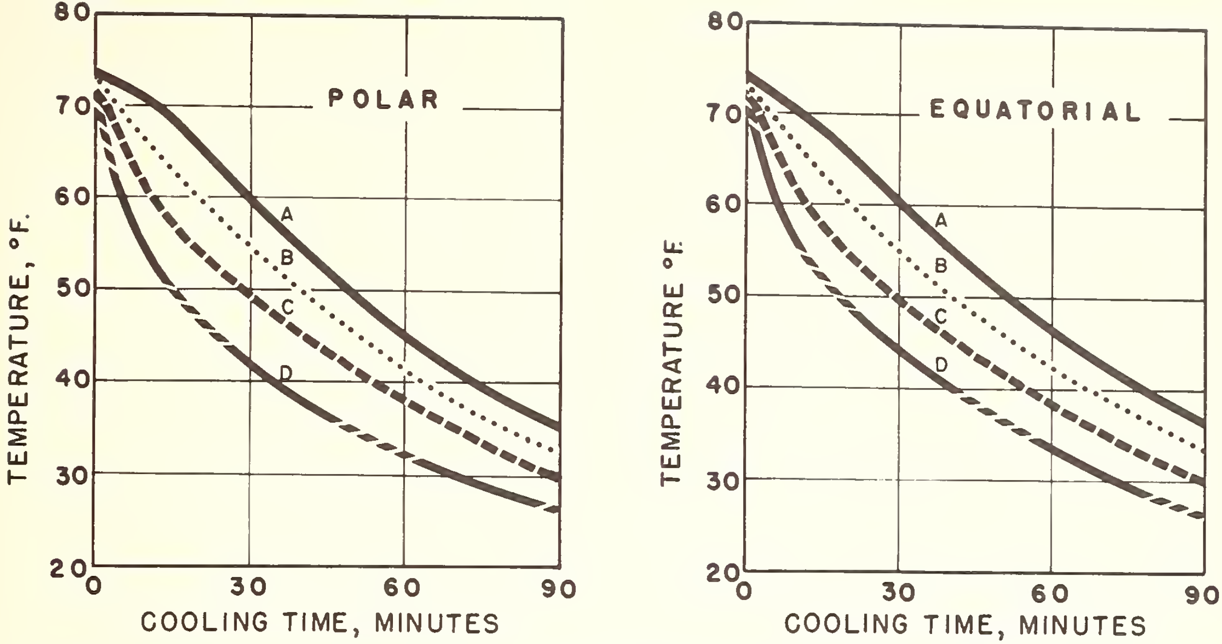

Figure 10.—Effect of direction of thermal probe insertion on measured temperature distribution during forced-air precooling of 500-pound bulk lots of Hamlin oranges at (A) fruit center, (B) half-radius, (C) theoretical mass-average, (D) surface.

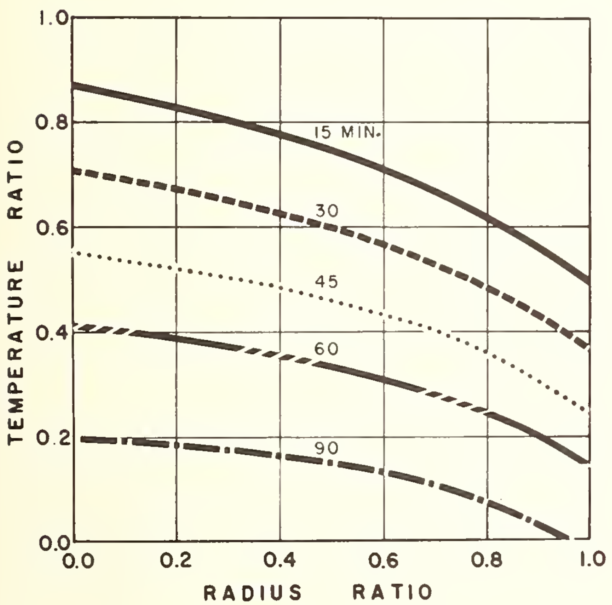

Figure 11.—Distribution of temperature from center to surface of Hamlin oranges during forced-air precooling. (From runs listed in test group 1 of table 2.)

poor contact with surrounding tissue, the polar probe produced a steeper thermal gradient along the probe and an apparently lower temperature at all points than the equatorial probe did.

Theoretical determination of heat transfer parameters for convection cooling requires that the cooling fluid be at a constant temperature. In the present experiments refrigeration capacity of the precooler was not sufficient to maintain a constant temperature throughout the cooling period. Two analytical procedures were used for comparisons between experimental and theoretical temperature responses in Hamlin oranges. Since experimental values generated with the third-degree polynomial equations—for which final minimum air temperature was used—did not fit well with theoretical values, Bennett and others (2) recomputed the data based on log mean air temperature. Much greater agreement between experimental and theoretical temperature response was then found. In other words, temperature distribution within the fruit could theoretically be predicted with Gurney and Lurie charts (13), provided log mean air temperature is the base. These results illustrate the difficulties in fitting experimental data obtained with nonhomogeneous, nonspherical fruits under nonstatic temperature conditions to theoretical curves for homogeneous spherical objects subjected to constant temperature throughout a cooling period.

System performance

The performance of this system was evaluated primarily on its cooling effectiveness, or "temperature response ratio" (product of cooling coefficient and cooling time); system efficiency as described by Bennett (1); and final mass-average temperature of the test specimen. Cooling coefficients ranged from 2.19 to 3.71 for bulk loads and from 0.04 to 0.86 for oranges packed in small containers. These quantities appear in table 4.

TABLE 4.—*Heat transfer characteristics and performance factors for representative tests on forced-air precooling of Hamlin oranges, Marsh and Foster grapefruit, and Orlando tangelos*[1]

Test run[2]	Final mass-average fruit temp.	Cooling coefficient	Surface heat transfer coefficient	Heat removed from fruit[3]: Calculated from equation X	Heat removed from fruit[3]: Calculated from equation XI	Efficiency
	° F.	*°F./(hr.) (° F.)*	*B.t.u./(hr.) (sq. ft.) (° F.)*	*B.t.u./(hr.) (lb.)*	*B.t.u./(hr.) (lb.)*	*Pct.*
145	44.4	2.77	14.44	21.4	35.7	42.2
149	40.9	3.68	15.03	22.9	32.1	23.8
150	41.3	2.75	13.38	24.8	37.9	25.8
151	41.7	2.62	8.20	26.6	27.8	27.8
152	41.4	2.69	14.79	21.5	38.4	22.4
153	38.7	3.20	15.95	22.8	34.6	13.2
161	47.6	2.19	18.07	22.9	38.7	22.7
175	41.6	2.66	15.83	23.2	30.4	24.1
177	41.2	2.83	15.26	23.0	30.0	23.9
179	40.9	3.35	16.24	25.3	32.2	27.3
186	46.0	2.65	11.93	21.7	27.7	43.0
187	44.7	2.85	10.61	21.1	22.2	41.7
188	46.5	2.59	11.89	25.9	30.3	51.4
189	49.3	2.76	11.92	29.3	34.2	58.2
191	45.4	2.87	11.20	25.3	28.3	48.6
194	36.8	3.14	13.04	29.1	19.9	28.9
200	35.9	3.18	12.13	28.6	27.8	29.9
201	34.7	3.64	10.81	30.2	21.5	31.2
203	35.7	3.38	14.53	30.4	31.2	30.2
206	36.2	3.66	17.18	30.6	31.8	30.4
229	33.0	3.71	9.51	34.0	25.4	35.6
230	32.8	3.50	8.42	31.5	34.4	32.7
234	54.3	.60	–	12.6	–	17.2
237	55.1	.75	–	12.3	–	17.4
239	64.5	.04	–	.7	–	1.0
240	54.3	.86	–	15.2	–	18.6

[1] Values computed as described in Appendix B.
[2] Treatments for these test runs are given in tables 8 and 9, Appendix C.
[3] Equations are given on p. 23.

TABLE 5.–*Performance index, operating cost, and cost index of performance for representative tests on forced-air precooling of Hamlin oranges, Marsh and Foster grapefruit, and Orlando tangelos*[1]

Test run	Performance index, ϕ	Operating cost	Cost index of performance, Ω
		Mills/lb.	*Mills/lb.*
145	50.5	0.348	0.69
149	35.8	.710	1.98
150	33.2	.661	1.99
151	34.6	.569	1.64
152	28.4	.689	2.43
153	19.5	1.373	7.04
161	22.6	.727	3.22
175	30.2	.684	2.26
177	31.2	.690	2.21
179	39.1	.655	1.68
186	48.8	.239	.49
187	50.4	.238	.47
188	56.9	.239	.42
189	62.7	.244	.39
191	57.9	.254	.44
194	44.5	.521	1.17
200	47.4	.509	1.07
201	55.0	.500	.91
203	49.8	.521	1.05
206	51.3	.529	1.03
229	66.6	.408	.61
230	59.7	.414	.69
234	7.8	.273	3.50
237	8.8	.267	3.03
239	1.0	.229	22.73
240	10.2	.332	3.26

[1] Values computed as described in Appendix B.

Also listed in table 4 are two other important variables: coefficient of surface heat transfer and amount of heat removed from fruit in a given time. Surface heat transfer coefficient varied from 8.20 to 18.07. Heat removed from fruit ranged from 21.1 to 34.0 B.t.u. per hour per pound for bulk oranges. System efficiency is based on the total amount of heat removed from a load of fruit during a test run and the refrigeration capacity of the precooler.

An index relating operating performance to cost per unit weight, the cost index of performance (table 5), evaluated experimental treatments. The two treatments obtained by regulating the fan and refrigeration equipment were (1) logarithmic mean air temperature and (2) mass-rate of airflow (table 6). Because load size, box type, fruit type, and initial fruit temperature could not be regulated, they are reported as variable rather than fixed treatments in table 8, Appendix C.

Calculations for results in tables 4, 5, and 6 are described in Appendix B.

Location and magnitude of mass-average temperature

Measurement of temperature in a fresh citrus fruit is actually the means of evaluating the amount of heat contained in the fruit or the rate of heat energy stored or released in a given time. If the temperature in the fruit is not uniform, as it is during moderately fast forced-air precooling, an average temperature must be used. One that relates the mass configuration to the thermal gradient within the fruit is the most appropriate. This is called the mass-average temperature. As defined by Smith and Bennett (29), the "mass-average temperature denotes a single value from the temperature distribution that would become the uniform product temperature under adiabatic conditions."

In those test runs for which the fruit time-temperature distribution was measured, the location and magnitude of the fruit mass-average temperature was determined as described by Smith and Bennett (29). The data were grouped by fruit type (fig. 12) and by direction of thermal probe insertion in the Hamlin orange group (fig. 13).

Fruit size and internal structure and thermal conductivity influence the distance from, and rate of approach of, the mass-average temperature locus to the mass center. This influence is observed by comparing the Marsh and Foster grapefruit with the Hamlin orange. However, since thermal conductivity among fresh citrus fruit is reportedly similar, only fruit size, fruit shape, and internal structure must influence the relation between mass-average temperature locus and mass center. If

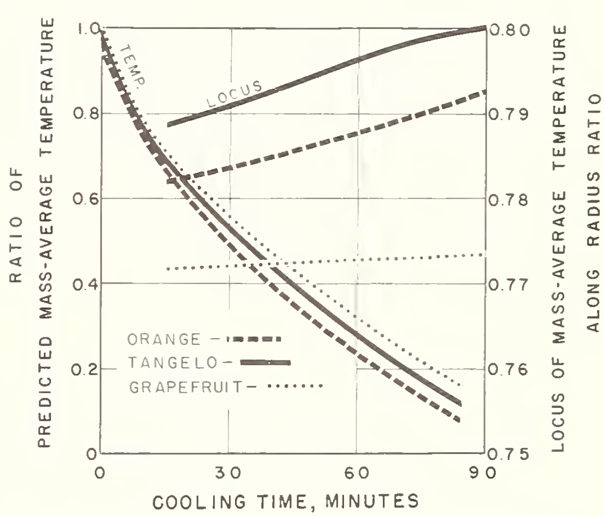

Figure 12.–Unaccomplished temperature change and location of mass-average temperature during forced-air precooling of Hamlin oranges, Marsh and Foster grapefruit, and Orlando tangelos.

TABLE 6.—*Operating data for representative second-season tests on forced-air precooling with Hamlin oranges, Marsh and Foster grapefruit, and Orlando tangelos*[1]

Test run	Log mean air temperature	Mass rate of airflow		Static pressure	Energy used	
		Per sq. ft. of coil face	Total per experimental unit		Fan motor	Condensing unit
	°F.	*1,000 Lb./(hr.)*[2]	*Lb./(hr.) (lb.)*[3]	*Inches H_2O*	*Kw. – Hr.*	*Kw. – Hr.*
145	39.8	12.48	32.81	4.50	6.55	7.35
149	38.2	13.41	70.56	4.40	6.79	7.41
150	37.6	10.98	57.77	4.60	6.33	6.88
151	35.3	4.94	26.00	4.60	4.99	6.38
152	38.5	12.96	68.15	4.50	6.70	7.07
153	35.0	14.79	155.58	4.43	6.86	6.87
161	43.2	19.55	102.82	3.60	7.34	7.20
175	38.1	13.78	72.50	4.08	6.83	6.79
177	37.7	12.98	68.28	4.33	6.93	6.82
179	37.8	13.61	71.60	4.25	6.74	6.88
186	42.2	9.62	25.30	2.25	2.82	6.82
187	41.6	7.92	20.84	2.30	2.67	6.92
188	44.2	9.58	25.19	2.28	2.79	6.85
189	47.6	9.51	25.01	2.30	2.79	7.04
191	42.5	8.62	22.68	2.33	2.80	7.37
194	32.1	15.06	79.24	1.95	3.23	7.18
200	33.2	10.17	53.50	2.28	2.93	7.25
201	32.4	8.35	43.94	2.35	2.77	7.15
203	33.3	13.74	72.28	1.95	3.24	7.18
206	35.2	15.20	79.93	2.00	3.17	7.40
229	27.3	6.87	36.12	.93	1.26	6.93
230	28.7	5.55	29.20	.98	1.18	7.06
234	28.9	–	–	1.00	1.18	6.57
237	27.2	–	–	1.00	1.03	6.71
239	27.7	–	–	.95	1.00	4.75
240	26.7	–	–	.95	1.10	6.86

[1] Value computed as described in Appendix B.
[2] 1,000 pounds of air per hour per square foot of coil face.
[3] Pounds of air per hour per pound of fruit.

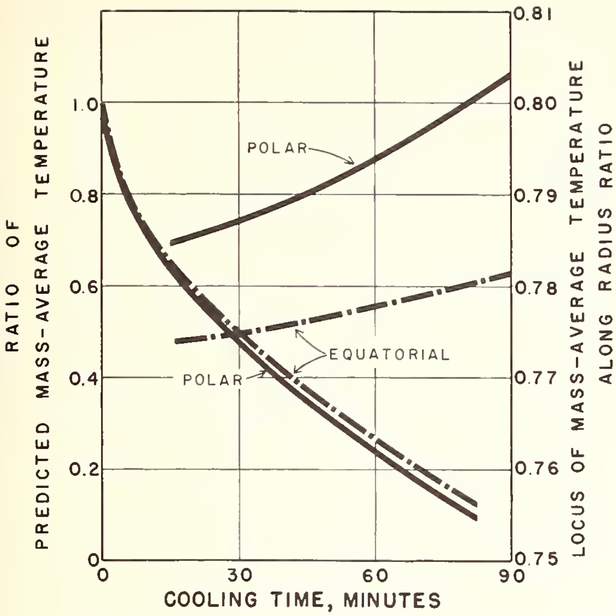

Figure 13.—Unaccomplished temperature change and location of mass-average temperature for equatorial vs. polar probe insertion during forced-air precooling of Hamlin oranges.

homogeneous spheres of equal size have similar thermal properties and moderate resistance to conduction heat transfer, each point of mass-average temperature should converge upon the point of mass center as uniform temperature is attained.

The curves for Orlando tangelos illustrate the error in assuming that different types of citrus fruit are homogeneous spheres: Tangelos have a hollow central axis, which shifts the center of mass closer to the surface than indicated on the chart (2); and tangelos, like grapefruit, are oblate spheroids. These characteristics cause measurements taken in the polar direction to include a greater error than those in spherical fruits of equivalent equatorial diameter. Consequently, with this fruit, the mass-average temperature did not converge upon the point where the fruit mass is divided equally.

The effect of shape is not as pronounced in grapefruit because of the grapefruit's relative size and greater height to diameter ratio. That ratio with respect to direction of probe insertion also appears to contribute to temperature response, as shown in figure 13, for solid, nearly spherical Hamlin oranges. The following are average location points of mass-average temperature for the precooling period:

Fruit	*Location* r^*
Orange	0.7856
Grapefruit	.7722
Tangelo	.7953

Because of the undesirable features mentioned above, probes should probably be inserted in the equatorial direction.

DISCUSSION

Performance

The fallacy of evaluating a precooling system on the basis of its cooling rate alone is seen by comparing run 179 with run 189 in table 4. The cooling coefficient indicates that run 179 is superior. Furthermore, the values of logarithmic mean air temperature (table 6) and of surface heat transfer coefficients (table 4) suggest that the environment for run 179 was more conducive to cooling. On the other hand, the efficiency value (table 4), show that run 189 is more than doubly superior to run 179. Further, the combined criteria of cooling rate and system efficiency (table 5) show that run 189 is substantially superior to run 179.

This superiority is chiefly attributable to doubling load size. But efficiency was more than doubled, and heat removed per pound in 189 was greater; therefore, there was another contributing factor: initial fruit temperature. Thus, doubling load size and raising initial fruit temperature produced the highest efficiency of all test runs. However, fruit temperature reduction was poor because the logarithmic mean air temperature of run 189 was approximately 10° F. higher than the average. Consequently, the highest total performance was obtained in run 229, which had half the load and a much lower system efficiency. Rating on this basis demonstrates the effect of arranging all contributing factors to provide operating conditions for maximum performance. The cost of performance criterion also shows run 189 superior. Similar evaluation of other test runs reveals the desirable and less desirable aspects of each.

Cost Index of Performance

Cost index of performance, as given in table 5, provides a more meaningful comparative evaluation than performance index alone because it measures performance in terms of energy used per pound of fruit cooled. Performance index alone does not take into account energy used. High performance normally corresponds to a low cost index. However, because the cost index is based upon the cost per pound, it does not always correspond with performance. Particularly, it was not a constant inverse proportion because the pounds of fruit cooled were varied.

The cost index of performance was used to evaluate all operating aspects of this type of forced-air precooling. Although the index is an indicator, it is not a precise measure of expected commercial conditions. A similar system more efficient than the experimental unit could be designed for commercial use.

Runs 175 and 177 exhibited results typical of the tests comparing place-packing and random-filling fruit in bulk lots. The two packing methods produced no observable differences in cooling rate.

The temperature at the mass-average point of oranges, grapefruit, and tangelos (table 4) reflects little difference between fruit types. These data are somewhat misleading because treatments were not similar among runs. The curves of figure 9 show that both the mass-average and center temperature of grapefruit generally lagged behind that of oranges and tangelos by approximately 5° F. This lag, attributed primarily to fruit size, demonstrates that fruit size related to type of fruit is necessary in evaluating the performance of a precooling system. Results of designated test runs 212 through 233 provide performance criteria for such an evaluation.

Performance.was poor with all types of containers. In some instances, reducing the bypass of air around the container might have improved performance. In any event, results strongly indicate that bulk cooling is better than cooling after the fruit has been packed in containers. Performance index of fruit precooled in bulk loads ranged from 19.5 to 66.6, and for oranges packed in small containers, from 1 to 10.2.

CONCLUSIONS

1. Depending upon size of fruit, initial fruit temperature, and other operating conditions, Hamlin oranges, Marsh and Foster grapefruit, and Orlando tangelos can be precooled with forced air to mass-average temperatures of 40° to 50° F. in an hour to an hour and a half.
2. Immediate or subsequent physiological injury to citrus fruit from rapid forced-air precooling is negligible provided the surface temperature does not go below about 28° F.
3. Desiccation of fruit is insignificant.
4. Within limits, performance is inversely related to rate of mass airflow. Approach velocities between 250 and 300 feet per minute produce optimum cooling in a forced-air precooling system operated as described.
5. For maximum performance the precooler should always be loaded to capacity, and all the air should pass through the product voids. Depth of fruit parallel to the direction of airflow should be from 12 to 24 inches.
6. Citrus fruits, packed in wirebound boxes or ventilated fiberboard cartons cool at about one-half the rate of fruits in bulk. Fruits in polyethylene bags or in nonventilated cartons cool more slowly, probably too slowly for commercial use.
7. Application of this concept of forced-air precooling, either as a batch or continuous-flow in-line system, is mechanically and economically feasible.

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APPENDIX A--SYMBOL NOTATION

Symbol	Description	Unit
A	fruit surface area per pound	sq. ft.
A_c	evaporator coil face area	sq. ft.
C	cooling coefficient	° F. per (hr.) (° F.)
c_p	specific heat	B.t.u. per (lb.) (° F.)
D	fruit diameter	ft.
E	system efficiency	percent
G	mass rate of airflow	lb. per (hr.) (sq. ft.)
h	surface heat transfer coefficient	B.t.u. per (hr.) (sq. ft.) (° F.)
k	thermal conductivity	B.t.u. per (hr.) (ft.) (° F.)
ℓ	length of one side of square bulk box	ft.
O	operating cost	mills per lb.
O_t	total operating cost	$
Q	heat removed	B.t.u. per (hr.) (lb.)
r^*	radius ratio—point along radius from center to surface	
t	temperature	° F.
Δ_t	temperature difference	° F.
TR	fruit temperature reduction	° F.
v	air velocity	ft. per min.
v_m	mean air velocity through fruit voids	ft. per min.
V	volume rate of airflow	c.f.m.
W	total weight of fruit cooled	lb.
Y	unaccomplished temperature change	--
Symbol of Subscripts		
a	air surrounding fruit	
c	fruit center	
fa	air surrounding fruit at end of test run	
i	initial fruit	
m	logarithmic mean	
ma	mass-average	
o	any point in fruit	
s	fruit surface	
Greek Symbols		
θ	time	hours
μ	dynamic viscosity	lb. per (hr.) (ft.)
ϕ	performance index	
ρ	density	lb. per cu. ft.
Ω	cost index of performance	mills/lb.

APPENDIX B--ANALYTICAL PROCEDURES

Fruit Temperature Distribution

Temperature of the fruit with respect to time and distance along the radius from center to surface was measured in selected test runs. The recorded data were analyzed by the procedure outlined by Smith and Bennett (29), to obtain coefficients for a third-degree polynomial equation with the general form,

$$Y = a + b_1 x_1 + b_2 x_2 + b_3 x_1^2 + b_4 x_2^2 + b_5 x_1^3 + b_6 x_2^3 + b_7 x_1 x_2 \qquad \text{I}$$

where,

$$Y = \frac{t_o - t_{fa}}{t_i - t_{fa}} \qquad \text{II}$$

time, in hours, is represented by x_1, radius ratio, r^*, is represented by x_2, and a is the constant and b_n are the coefficients listed in table 3.

Because air temperature was not constant throughout a test run, a fixed reference point was needed for calculating all temperature ratios. To simplify computations, air temperature at the end of each test run was used. Use of average values of air temperature would produce, in some instances, negative values of temperature ratio, Y, complicating analytical procedure. Because duplicating treatment conditions was difficult, only precise analyses of comparative evaluations among experimental test runs are presented. They should be useful, however, in predicting results of simulated operations in further research or in commercial application, since so many variables were tested. "Predicted" temperatures, illustrated in figures 9 and 10, and temperature ratio values shown in figures 11, 12, and 13, reflect the closest plot of data points corresponding to measured values within a particular grouping.

Mass-Average Temperature

The procedure developed by Smith and Bennett (29) was employed to determine the magnitude and location of mass-average temperature of that fruit in which temperature distribution was evaluated. The values of mass-average temperature listed in table 4 were computed from the equation—

$$t_{ma} = t_c - F\,(t_c - t_s) \qquad \text{III}$$

where F is the experimentally determined location of mass-average temperature, in terms of radius ratio, for the particular fruit at a specified time. This equation represents a simplified solution that assumes a linear temperature distribution from fruit center to surface. Solution of the equation—

$$Y(r^*) = a + b\,r^* + c(r^*)^2 + d(r^*)^3 \qquad \text{IV}$$

for specified radius-ratio values (where a, b, c, and d are derived coefficients applicable to designated cooling times) yields data for a family of curves, one for each designated cooling time and expresses the relationship of Y to r^*. A plot of these functions on rectangular coordinates (fig. 11) indicates that the deviation from linearity of the internal temperature distribution in Hamlin oranges, produces an error of about 2° F. (less than actual). This error, with slight deviation, is inherent in all runs, and therefore does not confound comparative evaluation among test runs.

Logarithmic Mean Air Temperature

Because of the characteristic decline in temperature of air surrounding the fruit with respect to cooling time, a logarithmic mean air temperature reflects a more nearly true value of average air temperature during a test run. The values of logarithmic mean air temperature listed in table 6 were computed by equation V. Subscripts 1 and 2 denote respective cooling times.

$$t_m = \frac{t_{a1} - t_{a2}}{\ln \left[\frac{t_{a1}}{t_{a2}}\right]} \qquad \text{V}$$

Similarly, because of the characteristic relation between fruit and air temperatures, the average difference between them is expressed in the logarithmic mean temperature difference, computed as follows:

$$\Delta t_m = \frac{(t_{ma1} - t_{a1}) - (t_{ma2} - t_{a2})}{\ln \left[\frac{t_{ma1} - t_{a1}}{t_{ma2} - t_{a2}}\right]} = \frac{\Delta t_1 - \Delta t_2}{\ln \left[\frac{\Delta t_1}{\Delta t_2}\right]} \qquad \text{VI}$$

Subscripts 1 and 2 denote respective cooling times.

Volume and Mass Rate of Airflow

The air velocity, measured with a vane anemometer at the inlet side of the evaporator coils, was converted to volume rate of airflow by multiplying velocity by coil face area (6.96 sq. ft.). Because obtaining accurate velocity measurements was difficult, the measured values, in volume airflow, were compared with the manufacturer's performance data at corresponding fan speeds and static pressure drops. The comparison showed that the measured data were consistently high.

Applying a correction factor of 0.75 (to exclude the area of the coils themselves) yielded a value that compared favorably with the fan performance data at all levels of airflow rate. This correction was accepted as valid and the volume rate of airflow was calculated by the equation—

$$\underline{V} = 0.75\ \underline{v}\ \underline{A_c} \qquad \text{VII}$$

Conversion to mass rate of airflow per square foot of free area (void space) perpendicular to the direction of flow was made with the equation—

$$\underline{G} = \frac{60\ \underline{V}\ \underline{\rho}}{\underline{\ell}^2 - \pi \frac{(\underline{D})^2}{(2)} \frac{(\underline{\ell})^2}{(\underline{D})}} \qquad \text{VIII}$$

or simplified—

$$\underline{G} = \frac{60\ \underline{V}\ \underline{\rho}}{\underline{\ell}^2\ (1 - \pi/4)}$$

Diameter of fruit, $\underline{D}$, was corrected for eccentricity as described by Turrell (30). Density, $\underline{\rho}$, was for dry air at $\underline{t_m}$.

Surface Heat Transfer Coefficients

One test of the amount of heat removed from fruit in a given time entailed the coefficient of surface heat transfer. This parameter was determined by assuming that the air forced through bulk lots of citrus fruit is analogous to a gas flowing normally to banks of staggered tubes. The heat transfer correlation from Jakob and Hawkins (21, p. 142) was used to compute the coefficients listed in table 6.

$$\frac{\underline{hD}}{\underline{k}} = 0.33 \left(\frac{\underline{v_m}\ \underline{D}\underline{\rho}}{\underline{\mu}}\right)^{0.6} \left(\frac{\underline{\mu}\ \underline{c_p}}{\underline{k}}\right)^{1/3} \qquad \text{IX}$$

The properties were taken for dry air at the log mean film temperature. Apparent mean velocity was computed on the basis of "free flow" void space area in a plane perpendicular to the direction of airflow. From equation VIII—

$$\frac{\underline{hD}}{\underline{k}} = 0.33 \left(\frac{\underline{GD}}{\underline{\mu}}\right)^{0.6} \left(\frac{\underline{\mu}\ \underline{c_p}}{\underline{k}}\right)^{1/3} \qquad \text{IXa}$$

Heat Removed From Fruit

Evaluation of the experimental precooler's performance entails determining heat removed from the fruit during a given test run. Two solutions were employed.

$$\underline{Q_1} = \underline{C_p}\ \underline{TR_{ma}} \qquad \text{X}$$

$$\underline{Q_2} = \underline{h}\ \underline{A}\ \Delta\ \underline{t} \qquad \text{XI}$$

In equation XI, $\Delta\ \underline{t}$ is the temperature difference between the fruit surface and the air surrounding the fruit. A specific heat of 0.9 B.t.u. per pound per ° F., was used in equation X.

Performance Index

The performance index proposed by Bennett (1) was adopted to evaluate test runs. As seen in equation XIV, it involves cooling effectiveness (product of cooling coefficient and cooling time), system efficiency, and final mass-average temperature.

Sainsbury (27) and Guillou (12), among others, have frequently used the cooling coefficient, as computed in equation XII, to describe cooling rate of products.

$$\underline{C} = \frac{\underline{TR_{ma}}}{\underline{\theta}\ \Delta\ \underline{t_m}} \qquad \text{XII}$$

System efficiency is based on the total amount of heat removed from a load of fruit during a test run, in relation to the refrigeration capacity of the precooler. For the present work, the percent system efficiency was calculated for the equation,

$$\underline{E} = \frac{\underline{WQ_1}}{540} \qquad \text{XIII}$$

Performance index, by test run, was thus determined by the equation,

$$\underline{\phi} = \frac{32\ \underline{E}\ \sqrt{\underline{\theta}\ \underline{C}}}{\underline{t_{ma}}} \qquad \text{XIV}$$

where $\underline{t_{ma}}$ is the mass-average temperature of the fruit at the end of the test run.

Cost Index of Performance

Operating cost per pound of fruit—

$$\underline{O} = \frac{\underline{O_t}}{\underline{W}} \qquad \text{XV}$$

was related to system performance by the equation,

$$\underline{\Omega} = \frac{\underline{O}}{\underline{\phi}} \times 100 \qquad \text{XVI}$$

APPENDIX C--TEST RUNS TABULATED

TABLE 7.—*Relation of airflow per foot of depth to type of fruit stacked*

Fruit	Static pressure	Airflow
	Inches-water	*Cubic feet per minute per square foot*
Tangerines	0.045	39
	.070	78
	.105	111
	.150	154
	.270	232
	.400	303
	.670	420
Grapefruit	.020	181
	.050	287
	.110	442
	.200	613
	.310	749
	.420	899
	.500	977
Hamlin oranges[1]	.035	74
	.120	183
	.200	238
	.260	254
	1.090	672
Valencia oranges	.020	59
	.050	167
	.150	348
	.260	478
	.360	560
	.450	658
	.550	720
	.650	794
	.750	850
Pineapple oranges	.080	220
	.090	236
	.140	335
	.230	414
	.340	608
	.650	799

[1] Fruit unusually soft. Settling occurred.

TABLE 8.—*Test treatments in 89 forced-air precooling tests with Hamlin oranges, Marsh and Foster grapefruit, and Orlando tangelos during second season*

Kind and size of fruit[1] and test run No.	Fruit load	Method of packing	Type of box[2]	Initial fruit temperature	Fan speed	Airflow[3]
	Lb.			°*F.*	*R.p.m.*	*Ft./min.*
ORANGES, 2.79 IN.						
145	1,000	Random	Wooden	69	1,400	990
146	1,000	do.	do.	91	1,400	821
147	1,000	do.	do.	72	1,400	435
148	1,000	do.	do.	75	1,400	952
149	500	do.	do.	71	1,400	1,065
150	500	do.	do.	72	1,400	870
151	500	do.	do.	74	1,400	386
152	500	do.	do.	68	1,400	1,028
153	250	do.	do.	71	1,400	1,162
154	250	do.	do.	68	1,400	904
155	250	do.	do.	68	1,400	379
156	250	do.	do.	67	1,400	1,095
157	250	do.	Mesh	73	1,400	1,808
158	250	do.	do.	75	1,400	1,545
159	250	do.	do.	71	1,400	390
160	250	do.	do.	73	1,400	1,009
161	500	do.	do.	76	1,400	1,564
162	500	do.	do.	74	1,400	1,106
163	500	do.	do.	68	1,400	510
164	500	do.	Mesh	70	1,400	1,421
165	1,000	do.	do.	68	1,400	1,320
166	1,000	do.	do.	76	1,400	1,320
167	1,000	do.	do.	72	1,400	998
168	1,000	do.	do.	76	1,400	427
169	1,000	do.	do.	70	1,400	1,256
ORANGES, 2.53 IN.						
170	500	do.	do.	68	1,400	1,568
171	500	do.	do.	67	1,400	1,568
172	500	do.	do.	72	1,400	1,054
173	500	Place-packed	do.	69	1,400	1,432
174	500	do.	do.	73	1,400	1,028
175	500	Random	Wooden	73	1,400	1,095
176	500	do.	do.	72	1,400	892
177	500	Place-packed	do.	70	1,400	1,028
178	500	do.	do.	73	1,400	859
ORANGES, 2.38 IN.						
179	500	Random	do.	70	1,400	1,072
180	500	do.	do.	70	1,400	862
181	500	do.	do.	71	1,020	799
182	500	do.	do.	68	1,020	656
183	500	do.	Mesh	72	1,020	1,080
184	500	do.	do.	60	1,020	795
185	500	do.	do.	77	1,020	795
ORANGES, 2.85 IN.						
186	1,000	do.	Wooden	73	1,020	769
187	1,000	do.	do.	70	1,020	630
188	1,000	do.	do.	80	1,020	769
189	1,000	do.	do.	87	1,020	769
190	1,000	do.	Mesh	75	1,020	889
191	1,000	do.	do.	76	1,020	694
192	1,000	do.	do.	80	1,020	889
193	1,000	do.	do.	89	1,020	889

See footnotes at end of table, p. 26.

TABLE 8.—*Test treatments in 89 forced-air precooling tests with Hamlin oranges, Marsh and Foster grapefruit, and Orlando tangelos during second season-Con.*

Kind and size of fruit[1] and test run No.	Fruit load	Method of packing	Type of box[2]	Initial fruit temperature	Fan speed	Airflow[3]
	Lb.			°*F.*	*R.p.m.*	*Ft./min.*
ORANGES, 2.82 IN.						
200	500	Random	Wooden	69	1,020	799
201	500	do.	do.	70	1,020	656
202	500	do.	do.	79	1,020	799
203	500	do.	Mesh	71	1,020	1,080
204	500	do.	do.	72	1,020	795
205	500	do.	do.	86	1,020	1,080
224	500	do.	do.	73	670	716
225	500	do.	do.	73	670	518
226	500	do.	do.	85	670	716
227	1,000	do.	do.	73	670	352
228	1,000	d0.	do.	74	670	592
229	500	do.	Wooden	73	670	532
230	500	do.	do.	69	670	431
231	500	do.	do.	87	670	532
232	1,000	do.	do.	73	670	457
233	1,000	do.	do.	77	670	289
GRAPEFRUIT, 3.95 IN.						
194	500	do.	Mesh	73	1,020	1,178
195	500	do.	do.	70	1,020	810
196	500	do.	do.	80	1,020	1,178
197	500	do.	Wooden	73	1,020	844
198	500	do.	do.	70	1,020	690
199	500	do.	do.	86	1,020	844
218	500	do.	do.	69	670	570
219	500	do.	do.	72	670	458
220	500	do.	do.	86	670	570
221	500	do.	Mesh	69	670	810
222	500	do.	do.	69	670	574
223	500	do.	do.	86	670	810
TANGELOS, 2.38 IN.						
206	500	do.	do.	72	1,020	1,192
207	500	do.	do.	71	1,020	832
208	500	do.	do.	87	1,020	1,192
209	500	do.	Wooden	73	1,020	776
210	500	do.	do.	71	1,020	645
211	500	do.	do.	86	1,020	776
212	500	do.	Mesh	71	670	772
213	500	do.	do.	71	670	551
214	500	do.	do.	86	670	772
215	500	do.	Wooden	71	670	499
216	500	do.	do.	72	670	412
217	500	do.	do.	86	670	499

[1] Average diameter of Hamlin oranges, Marsh and Foster grapefruit, and Orlando tangelos.
[2] Wooden=standard wooden-bottom box.
Mesh=wire-mesh-bottom box.
[3] Approach velocity to evaporator coil. Corrected as described in Appendix B.

TABLE 9.—*Test treatments for 25 forced-air precooling tests to determine effectiveness of cooling oranges in various types of containers, second season*

Type of container and test run	Capacity of container	Fruit: Variety	Fruit: Average diameter	Initial fruit temperature	Load
	Lb.		*In.*	°*F.*	*Lb.*
WIREBOUND BOX					
234	54 - 57	Hamlin	2.75	69	710
235	54 - 57	do.	2.75	84	710
241	54 -57	Parson Brown & Pineapple	2.75	71	690
242	54 - 57	do.	2.75	83	690
245	54 - 57	Valencia	3.00	83	700
246	54 - 57	do.	3.00	71	700
247	54 - 57	do.	3.00	85	700
248	54 - 57	do.	3.00	71	700
249	54 - 57	do.	3.00	85	700
255	54 - 57	do.	2.38	71	790
256	54 - 57	do.	2.38	84	790
FIBERBOARD CARTON					
236	33 - 38	Hamlin	2.63	73	725
237	33 - 38	do.	2.63	70	725
238	33 - 38	do.	2.63	82	725
243	33 - 38	Valencia	3.00	77	680
244	33 - 38	do.	3.00	84	680
252	33 - 38	do.	3.00	83	770
253	33 - 38	do.	3.00	75	770
254	33 - 38	do.	3.00	82	770
POLYETHYLENE BAGS IN BAGMASTER CARTONS					
239	8	Hamlin	2.63	65	630
POLYETHYLENE BAGS—LOOSE					
240	8	Hamlin	2.63	71	600
250	8	Valencia	3.00	87	640
251	8	do.	3.00	70	640
257	8	do.	2.38	87	740
258	8	do.	2.38	71	740

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