ARS 52-41
November 1969

FORCED-AIR PRECOOLING OF RED DELICIOUS APPLES

Temperature Response and Physiological Effect

Agricultural Research Service
UNITED STATES DEPARTMENT OF AGRICULTURE

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SUMMARY

Two lots of Red Delicious apples were cooled in bulk in an experimental forced-air precooler. Observations of quality were made after 7 and 14 days on apples sampled at 15-minute intervals during cooling periods of 90 minutes. U.S. No. 1 apples were used for the tests. Air and fruit temperatures were recorded periodically throughout the four test runs, two runs for each lot. Average cooling air temperature ranged from 22° to 28° F. Velocity of the air approaching the fruit ranged from 200 to 800 feet per minute (f.p.m.). Cooling rate was evaluated in terms of time-temperature response, cooling coefficient, half-cooling time, and amount of heat removed per pound. Fruit quality was evaluated in terms of desiccation, color, decay, freezing injury, and bruises during precooling and subsequent holding. Precooler efficiency was evaluated in terms of the ratio of total heat removed from the fruit to the cooling capacity available.

Mass-average temperature of the apples was reduced from 85° to 45° F. in 30 minutes, and to 29° in 1 hour, with the cooling air circulating at an approach velocity of 400 f.p.m. Reducing air velocity to 200 f.p.m. resulted in cooling from 88° to 58° in 30 minutes, and to 39° in 1 hour. Increasing the approach velocity of the cooling air from 400 to 800 f.p.m. did not improve fruit cooling response.

Weight loss in the fruit from desiccation during precooling was insignificant. Weight loss averaged about 2.5 percent after 7 days, and about 5 percent after 14 days. Color appeared to improve during the 14-day holding period. Decay increased slightly but was not significant in either inspection. Appreciable freezing injury was observed at both the 7- and 14-day inspections in apple samples that were cooled for 50- and 90-minute periods in run 1. Although freezing injury appeared at the 14-day inspection in some apples of run 2, it was not attributed to precooling effects. Bruises appeared after 14 days in the first test lot and after 7 days in the second lot. Total system cooling efficiency ranged from 30 to 45 percent.

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INTRODUCTION

Field heat must be removed from apples before storage or during the initial storage period to assure satisfactory storage life and maintenance of fruit quality. This cooling may be accomplished by hydrocooling or by some form of air cooling. Ideally, the fruit should be cooled to the desired storage temperature as rapidly as possible. Some growers hydrocool their fruit before storing it. Although hydrocooling is the best method for cooling fruit as quickly as possible after harvest, it requires a large capital investment in heavy-duty mechanical refrigeration equipment, or a considerable expenditure for ice. For this reason, most apples sold as fresh fruit are cooled from field to storage temperature in the storage facility. Most commercial storage operators have adopted this practice because "...it represents a good compromise between costs and ideal procedure." 3/

Cooling with air is generally thought of as a slow process, and indeed it is, when large quantities of apples are air cooled in a storage room with poor air circulation and inadequate refrigeration. Fast, yet economical, air cooling can be accomplished by forcing the air at some temperature below the freezing point of the fruit through the void spaces of the fruit in bulk. In this way, rapid heat transfer is accomplished with relatively small volumes of air.

One of the primary disadvantages of using air below the freezing point of the fruit is the possible danger of freezing the fruit. This would not be a problem in a commercial system provided the relationship between the three factors was clearly understood and the system was designed accordingly. In an air cooled system, the surface temperature of the fruit is a function of the air temperature, the air velocity at the surface, and the exposure time. This study was conducted to investigate effects of forced-air precooling on temperature response and physiological condition of Red Delicious apples. Factors measured were: (1) cooling rate, (2) relationship of fruit surface to air temperature, (3) weight loss by desiccation, and (4) physiological condition of fruit after holding for 7 days and 14 days.

EXPERIMENTAL PROCEDURE

Four tests, two in the early season and two in the late season, were run using two separate lots of freshly harvested Red Delicious apples. The first test lot consisted of approximately 500 pounds of good quality packinghouse rejects, and one bushel of U.S. No. 1 fruit. Ten mesh bags, each containing 10 pounds of fruit from the rejects and the U.S. No. 1 lot, were scattered within the bulk. Fruit in these bags was used for the physiological and temperature observations. The second lot consisted of approximately 400 pounds of packinghouse rejects, including 10 mesh bags containing 30 U.S. No. 1 apples each. A standard wooden pallet box was used as a bulk container.

3/ Sainsbury, G. F. Cooling apples and pears in storage rooms. U.S. Dept. Agr. Market. Res. Rpt. No. 474, 55 pp. 1961.

The research was carried out in the experimental forced-air precooler described by Soule, and others. 4/ Treatment conditions and operating data for the four test runs are listed in table 1. The following test procedure was used:

(1) The precooler was cooled to the temperatures shown in table 1 before apples at ambient packinghouse air temperature (85-88° F. for runs 1 and 2, 78° for runs 3 and 4) were put into the cooling chamber.

(2) Duplicate bags of apples were removed at 1/4-hour intervals through 1 hour of the test; then the remaining were removed after 1 1/2 hours.

(3) One of each set of duplicate bags was stored for 14 days at 75°; the other bag of each set was stored for 7 days at 40°, then 7 days at 75°.

(4) Apples were weighed before and after precooling, and after the 7- and 14-day holding periods.

(5) Each bag of apples was completely inspected at the end of the 7- and 14-day periods.

Table 1.--Operating data for forced-air precooling test runs on Red Delicious apples

Run	Airflow		Power			Precooling time	Air temperature	
	Approach velocity	Volume	Fan	Refrig.	Total		Initial	Av.
	F.p.m.	C.f.m.	Kw.	Kw.	Kw.	Hrs.	°F.	°F.
1	400	6,400	0.72	6.68	7.40	1.5	10	24
2	200	3,200	0.67	5.91	6.58	1.5	13	28
3	800	12,800	2.49	7.19	9.68	1.5	10	25
4	400	6,400	0.96	6.23	7.19	2.0	12	22

Fruit temperature was measured at the center, at the mass-average point, and on the surface of each of two uniformly sized U.S. No. 1 apples. Air temperature was measured at the inlet and outlet side of the cooling coils. Rate of airflow was measured by taking 63 readings with a vane anemometer at traverse points on the discharge side of the cooling coils. The airflow values are reported in terms of linear velocity of the air approaching the fruit, and volume rate of airflow.

4/ Soule, J., Yost, G. E., and Bennett, A. H. Experimental forced-air precooling of Florida citrus. U.S. Dept. Agr. Market. Res. Rpt. No. 845, 27 pp. 1968.

The runs, and results obtained from them, were complicated by several factors: (1) Two different lots of fruit were used in the tests; (2) rates of airflow chosen for runs 1 and 2 resulted in considerable freeze damage to the fruit, hence higher rates were used in runs 3 and 4; (3) initial fruit temperatures were packinghouse ambient air; thus, the late season runs commenced at temperatures 7° to 10° F. lower than those in the early season; and (4) ambient air temperatures outside the precooler and the configuration of the load inside also changed from one run to another, thus leading to variations in power used in initial and average air temperatures among runs.

RESULTS

Air and fruit temperatures from which cooling rate data were calculated are shown in table 2. Cooling rate data, in terms of cooling coefficients, half-cooling times, and the amount of heat removed per pound of fruit, for each of the four test runs are presented in table 3. The cooling coefficient is the slope of the linear portion of each mass-average time-temperature response curve occurring within the 15- to 45-minute time interval. Time-temperature response curves for each run are illustrated in figure 1.

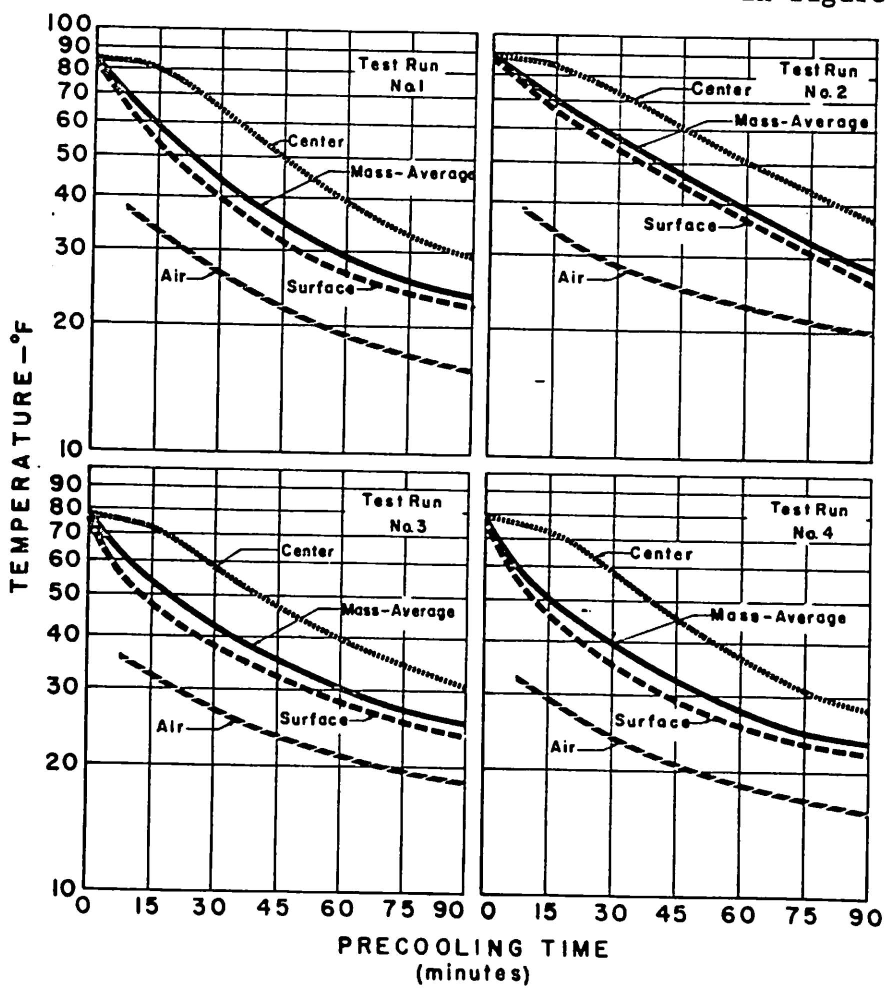

Figure 1.--Time-temperature response of Red Delicious apples to forced-air precooling.

Table 2.--Air and fruit temperatures during 4 test runs with forced-air precooling of Red Delicious apples (°F.)

Cooling time (hours)	Air in test chamber				Fruit											
					Surface				Center				Mass average 1/			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
0	8.6	13.8	12.3	12.5	85.0	88.5	78.0	78.0	85.0	88.5	78.0	78.0	85.0	88.5	78.0	78.0
0.125	38.5	38.4	35.0	33.0	66.4	75.6	55.3	56.2	84.8	88.5	76.8	77.3	70.1	78.1	59.6	60.4
0.250	32.8	33.5	31.3	29.5	53.2	66.1	46.5	45.3	80.8	85.0	72.5	73.8	58.7	69.9	51.7	51.3
0.375	28.9	30.9	31.0	26.3	46.3	59.8	44.5	39.9	73.0	79.0	65.8	66.8	51.6	63.6	48.8	45.3
0.500	26.3	28.8	27.5	24.0	40.5	54.6	39.7	35.2	64.8	72.5	58.3	58.8	45.4	58.2	43.4	39.9
0.625	24.2	29.3	25.5	23.0	35.6	50.0	35.5	31.8	57.0	66.5	53.8	51.8	39.9	53.3	39.2	35.8
0.750	22.0	26.5	23.5	21.3	31.3	46.3	32.7	29.1	50.5	61.0	48.5	46.0	35.1	49.2	35.9	32.5
0.875	20.8	24.7	22.5	20.0	28.2	42.0	30.7	27.0	44.8	56.0	44.0	41.0	31.5	44.8	33.4	29.8
1.000	20.0	23.0	20.8	19.5	25.7	35.6	28.3	25.1	40.3	51.3	40.0	37.0	28.6	38.7	30.6	27.5
1.125	17.4	23.0	20.0	18.3	25.4	32.9	26.6	24.5	36.5	47.3	37.0	33.8	27.6	35.8	28.7	26.4
1.250	17.3	21.8	19.3	17.0	24.0	30.0	24.9	23.4	33.5	43.0	34.0	31.3	25.9	32.6	26.7	25.0
1.375	17.0	20.9	18.6	16.4	23.2	27.9	24.1	22.6	31.0	39.8	32.3	29.0	24.8	30.3	25.7	23.9
1.500	15.5	19.8	18.3	15.8	22.8	26.3	23.6	22.1	29.8	36.3	31.0	28.0	24.2	28.3	25.1	23.3

1/ Calculated by linear interpolation on the basis of 0.80 R = mass average.

Table 3.--Cooling rate criteria for forced-air precooling bulk lots of Red Delicious apples

Test run 1/	Cooling coefficient	Half-cooling time	Heat removed per lb. per hr.	Efficiency
	°F. per (hr.)(°F.)	Minutes	B.t.u.	Percent
1	2.45	17	48.5	45
2	1.43	29	42.8	40
3	1.98	21	40.7	30
4	2.34	18	43.5	32

1/ Respective treatments are outlined in table 1.

Slope of the curve was calculated on the basis of the difference between the arithmetic average of the fruit and air temperatures. Half-cooling time is the natural logarithm of one-half (0.69) divided by the cooling coefficient. Heat removed per pound of fruit was calculated by multiplying the mass-average temperature reduction per hour by the specific heat of the fruit (taken as $C_p = 0.9$). The efficiency values listed in the table indicate the effectiveness of the system in removing heat from the fruit with respect to the available refrigerating capacity. From manufacturers' specifications, this capacity was assumed to be 54,000 B.t.u./hr. The efficiency figures shown represent the total heat removed from the fruit in 1 hour (based on pounds of fruit cooled) divided by 54,000 B.t.u./hr.

The initial fruit temperature, shown in figure 1, is an important consideration in forced-air precooling. The primary difference between test runs 1 and 4 was in this initial temperature (table 2). The surface of the fruit in run 4 was cooled to 27.5° F. in 60 minutes, compared with 28.6° in run 1.

Table 4 shows weight loss and quality observations. While some weight loss resulted from fruit decay during the holding period, weight loss by desiccation during precooling was negligible. Significantly, there was almost no weight loss, and in one case a slight weight gain, during precooling of the late season fruit. Weight loss during holding also decreased for the late season fruit. Weight loss was kept low during holding at 40° F. for 7 days, but significant weight loss occurred during 7- and 14-day holding periods at 75°. Length of precooling period or test treatment did not affect fruit ground color. Color changes shown in table 4 are the effects of the holding period rather than of precooling. Decay was slight in fruit refrigerated at 40°.

Some fruit began to decay after 14 days at shelf life temperature of 75° F. The significant amount of freezing injury on fruit cooled for 1 hour under the conditions of run 1 probably resulted from the reduction of surface temperature to 25.7° after 1 hour of cooling (table 2). However, no freezing injury was observed after a similar temperature reduction in run 4. In the early season tests, bruises were slight on fruit refrigerated for 7 days. Bruise damage began to appear significantly on fruit held for 14 days at shelf

Table 4.--Weight loss and quality observations of forced-air precooled Red Delicious apples at 7(A) and 14(B) days

Precooling period (min.) and holding period 1/	Number of fruit in sample	Sample weight	Weight loss: During precooling	Weight loss: Precooling and holding		Quality observations: Color 2/		Decay		Freezing injury 3/		Bruises	
		Grams	Grams	Grams A	Grams B	A	B	No. of fruit A	No. of fruit B	No. of fruit A	No. of fruit B	No. of fruit A	No. of fruit B
RUN 1													
15-I	37	5,123	1	156	245	YG	Y	0	1	0	0	0	14
15-II	33	4,895	4	23	136	G	YG	0	2	0	0	0	8
30-I	40	5,375	12	159	340	YG	Y	1	6	0	0	1	16
30-II	41	4,584	9	27	141	G	GY	0	1	0	1	0	10
45-I	41	5,323	4	144	231	YG	YG	0	2	0	1	2	23
45-II	34	4,614	13	24	127	G	GY	1	6	1	0	0	12
60-I	31	4,948	2	137	222	YG	Y	0	2	14	13	0	16
60-II	30	5,040	14	23	140	G	GY	0	1	9	13	0	16
90-I	30	4,843	4	148	1,397	YG	Y	8	20	17	6	2	4
90-II	33	5,197	6	17	131	G	GY	0	5	25	22	2	6
RUN 2													
15-I	35	5,404	17	149	236	YG	Y	0	1	0	0	0	20
15-II	33	4,803	13	26	142	G	GY	0	5	0	1	0	10
30-I	36	5,166	14	136	217	YG	Y	0	4	2	1	9	25
30-II	36	4,766	19	29	137	G	GY	0	1	0	2	2	28
45-I	35	5,176	6	153	250	YG	Y	0	5	4	8	15	22
45-II	33	4,732	12	19	109	G	GY	0	2	1	8	4	16
60-I	33	4,898	6	139	223	YG	Y	0	3	0	4	17	20
60-II	33	5,056	9	22	158	G	GY	0	0	1	6	6	21
90-I	35	5,227	4	147	364	YG	Y	1	1	1	7	24	17
90-II	33	4,673	6	12	267	G	Y	1	1	3	1	14	30
RUN 3													
15-I	30	4,785	-2	83	310	GY	Y	1	2	0	0	23	24
15-II	30	4,666	-2	30	125	YG	GY	0	2	0	0	10	20
30-I	30	4,763	0	76	160	GY	Y	0	1	0	0	28	20
30-II	30	4,702	0	34	130	YG	GY	0	0	0	0	12	21
45-I	30	4,951	0	71	149	GY	Y	0	2	2	3	17	21
45-II	30	4,447	0	31	117	YG	Y	0	1	0	0	10	27
60-I	30	4,351	0	59	129	GY	Y	0	0	0	0	26	30
90-I	30	4,862	1	73	642	GY	Y	3	4	18	17	9	9
RUN 4													
15-I	30	5,150	1	83	176	GY	Y	0	5	0	0	27	20
30-I	30	4,970	2	79	167	GY	GY	0	0	2	1	19	29
45-I	30	4,568	2	72	158	GY	GY	0	2	0	0	21	26
45-II	30	4,511	0	40	143	YG	GY	0	1	0	0	7	29
60-I	30	4,495	2	62	143	GY	GY	0	0	0	0	23	30
60-II	30	4,789	0	28	100	YG	GY	0	1	3	3	13	23

1/ I=held at 75° F. for 14 days; II=held at 40° for 7 days and 75° for 7 days.
2/ G=green; GY=greenish yellow; YG=yellowish green; Y=yellow.
3/ Browning of skin caused by frost or freeze injury.

life temperature. In the late season tests, bruising appeared significantly in all cases, but was less on fruit refrigerated for 7 days.

DISCUSSION

Cooling Rate

The superior performance of test run 1 in every respect is the result of a favorable combination of airflow rate and high initial fruit temperature. An approach velocity of 200 f.p.m. proved inadequate, while that of 800 f.p.m. failed to increase the cooling rate. Actually, the cooling rate, as a function of surface heat transfer, would increase with an increase in velocity, provided the air temperature remained the same. In this case, because available refrigeration was not sufficient to handle the extra load imposed by the fan, doubling the approach velocity from 400 to 800 f.p.m. produced a small gain in air temperature and a consequent reduction in cooling rate. This response is shown by data on test runs 3 and 4 in table 2.

The effect of initial fruit temperature is shown by comparing run 1 with run 4. Initial fruit temperature was the principal treatment difference between the two tests. Because of the higher initial temperature of the fruit in run 1, rate of heat removal and subsequent system efficiency were higher than for run 4.

Air Versus Fruit Surface Temperature

In forced-air precooling, where the air is cooled to a temperature substantially below the freezing point of the fruit, the relationship between cooling time and air and fruit surface temperature is important. The possibility of freeze damage cannot be ignored and commercial systems must be designed to avoid it.

Examination of table 2 and figure 1 shows that the surface temperature of the fruit with the higher cooling rate (runs 1 and 4) was probably below the freezing point after 1 hour of cooling. The high incidence of freezing injury on fruit of run 1 after 60 minutes of cooling bears this out. Although the absence of freezing injury on fruit treated similarly in run 4 appears to contradict this observation, the ground color of this fruit was noticeably more yellow, indicating greater maturity than the fruit in run 1. Because of this maturity, the fruit may have been less susceptible to surface freeze or frost injury.

Considering all factors, a forced-air precooling system designed like the one for run 1 should have a maximum allowable cooling time of 45 minutes. Probably because of the slow cooling rate associated with low airflow, freeze damage was not observed after 90 minutes of cooling for test run 2.

Weight Loss

Weight loss of apples by desiccation during precooling was very slight in the early tests and almost nonexistent in the late season tests. Desiccation and decay contributed to weight loss during holding, with most loss occurring after 14 days without referigeration. Weight loss during precooling was not influenced by cooling time or by rate of airflow.

Physiological Effects

Quality observations indicate that forced-air precooling of apples, in a system with air at temperatures several degrees below the freezing point of the fruit, does not produce undesirable effects provided the fruit is not allowed to freeze. The value of refrigerating the fruit, even for short periods of 7 days or less, is also demonstrated.