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Air Circulation and Temperature Conditions in Refrigerated Carloads of Fruit

By H. M. NEWELL AND J. W. LLOYD

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Air Circulation and Temperature Conditions in Refrigerated Carloads of Fruit

By H. M. NEWELL and J. W. LLOYD*

REFRIGERATED transportation of Illinois fruits has become increasingly important during the past ten or twelve years as heavier production and keener competition have forced wider distribution with consequently longer hauls. Altho the motor truck has become an important factor in the movement of Illinois fruits, refrigerated carlot shipments constitute the greater part of the movement of strawberries, peaches, and early apples from the state. During 1931, 5,306 carloads of peaches were shipped by rail from Illinois producing points. A large percentage of these shipments moved to destinations 48 hours or more distant from the loading points, and practically all of them moved under refrigeration.

Investigations of the problems involved in handling and transporting Illinois fruits and vegetables have been under way at the Illinois Experiment Station since 1926. Special attention has been given to the refrigeration of strawberries, peaches, and summer apples in transit. In the earlier studies^{11*} rapid cooling was shown to be essential to the most efficient handling of these commodities, and temperature studies made on several shipments indicated that air circulation plays an important part in efficient refrigeration. An examination of the literature, however, revealed a lack of definite information concerning the factors that influence air circulation in refrigerator cars, the direction and rate of movements of air currents within the cars, and the relation of air movement to temperature conditions thruout the load. It was to shed further light on some of these questions that the studies reported herein were made.

REVIEW OF PREVIOUS INVESTIGATIONS

Circumstances do not warrant a complete review of the literature pertaining to perishable transportation. Discussions of historical interest only and most articles based on opinions and suppositions have been eliminated from consideration. Except in a few cases the articles reviewed are based on experimental evidence or on practical experience

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¹¹These figures refer to literature citations, see page 224.

with problems of this nature. Discussions of articles dealing with mechanical refrigeration and unusual schemes for perishable refrigeration are not included.

Limited Information on Air Circulation

Lorion^{12*} wrote, "There appears to be a lack of real information and reliable understanding of what occurs in a refrigerator car under either standard refrigeration or standard ventilation." He stated further that attempts have been made to determine the velocity of the air in various parts of loads under ice but that such tests have been inconclusive.

Pole-Evans and Griffiths^{17*} traced the convection currents in refrigerator cars equipped with end ice bunkers. They concluded that these currents must leave stagnant air spaces with any practical type of end ice bunkers.

In discussing heat transfer during the cooling of a ship's cargo of apples, Smith^{19*} stated that by analogy with known cases it may be assumed that the rate of heat transfer depends to some extent on the velocity of the air, but that no useful data exist regarding the rate of transfer of heat from a stack of fruit to a stream of air passing thru it.

Gibson and Graff^{4*} studied air circulation in a refrigerator car under ventilation by means of smoke and anemometers. They reported velocities as low as 5 to 10 feet per minute at some points in the car. They gave no description of the instrument used, but stated that in one position it ran both ways, indicating that it was a vane anemometer. It is doubtful if much significance can be attached to vane anemometer readings as low as this.

Transfer of Heat From Lading to Ice by Air Circulation

Smith^{19*} made an analytical study of temperature gradients during cooling in refrigerated ship holds. He found that with a constant rate of air circulation an increase in the coefficient of heat-transfer, such as might be obtained by a more open type of package, increased somewhat the average rate of cooling and resulted in a greater variation of temperature thruout the stack during the early stages of cooling. With a constant coefficient of heat-transfer an increase in the rate of air circulation had little effect on the average rate of cooling but considerably reduced the variation of temperature inside the stack. The range of variation of temperature was approximately inversely proportional to the rate of air movement. Smith was dealing with forced air circulation and consequently with somewhat higher velocities than normally occur in refrigerator cars. He also concluded that an increase

in the amount of refrigeration available, coupled with an increase in the rate of air movement, would simultaneously secure both more rapid and more uniform cooling. He showed mathematically that the rate of heat-transfer is proportional to the logarithmic mean of the temperature difference between the material and the air.

Hill, Graham, Wright, and Taylor^{10*} pointed out that the cooling of a refrigerated shipment is dependent on the circulation of air within the car. Andrews^{1*} stated that when air is the cooling medium, over 50 cubic feet are required to remove one heat unit from the fruit if a one degree rise in air temperature is produced. This does not take into consideration any cooling that may be produced by evaporation.

Lorion^{12*} stated that as air fills all the unoccupied spaces in the car it comes into intimate contact with the load, cools the exterior of the packages first, and then moves into the package thru any openings that may be present or effects a heat-transfer thru the surface of the box. McKay^{14*} attributed part of the retardation of refrigeration by paper wrappers on cantaloupes to the tendency of the paper to obstruct the circulation of cold air around and thru the crates. Andrews^{1*} emphasized the importance of considering the individual fruits rather than the packages as the units around which air should circulate. Overholser and Moses^{15*} reported that air temperatures in a car of grapes being precooled with circulating fans did not become so low as those in a car of pears under the same precooler, probably because the air was more completely circulated about the grapes, thus effecting a more rapid transfer of heat. It would seem desirable, therefore, to have fruit packages as open as possible to encourage air circulation in direct contact with the fruit.

It seems reasonable that the direction and rates of circulation in refrigerator cars vary not only between different points within the car but also from time to time at a given location within the car. Lorion^{12*} claimed that at the beginning of a trip when the load is still warm there will be the maximum tendency for the air to rise immediately upon leaving the ice chamber, but that as this part of the load cools, the vertical rise at that point slows down and there tends to be an equalization of upward velocities between points near the bunker and at the center of the car.

Hawkins^{8*} pointed out that the ice in the bunkers must be sufficient to absorb the heat leakage into the car thru the walls, ceiling, and floor, and to overcome both the field heat of the lading and the vital heat or heat of respiration of the fruit. He stated that no set formula can be developed for the amount of heat to be absorbed in cooling down commodities inasmuch as this varies with the product and the temperatures

at which it is held. He described the vital heat as due to the breaking down of glucose into carbon dioxid and water. The heat of combustion of glucose is 14.28 B. t. u. per gram. For each gram of glucose broken down 1.465 grams of carbon dioxid would be liberated. From these constants he calculated the heat of respiration of a number of products at various temperatures, using Gore's determinations^{5*} of the amount of carbon dioxid given off by fruits at various temperatures.

Griffiths and Awbery^{6*} found that at a temperature of 20° C. sound apples generated heat at the rate of about .012 calorie per second per kilogram, or that for an apple of average size (2½ inches in diameter) the rate of heat generation was .0015 calorie per second.

Effect of Car Design and Equipment on Air Circulation

Air circulation in refrigerator cars apparently is dependent to a large extent on the design and equipment of the cars themselves. Pennington^{16*} stated that a combination of basket bunkers, insulated bulkheads, and floor racks produced a circulation of air which was not obtained in a car having a box bunker, an open bulkhead, and a bare floor. Winterrowd^{21*} stated that the temperature of the circulating air is affected by the type and size of the ice bunker.

Hill, Graham, Wright, and Taylor^{10*} found that the divided wire basket bunker refrigerated loads as well as standard wire basket bunkers of larger ice capacity, and that the former were more economical in the melting of ice. The divided basket bunker is constructed to allow air circulation in contact with a larger amount of ice surface. The results of this test agreed with Sweeley's explanation^{20*} that the value of basket ice bunkers results from their exposure of a large ice surface. He stated that rapid melting is dependent on the amount of ice surface exposed, and that the efficiency of an ice bunker depends not so much on its size as on its design to permit the maximum air circulation thru and around the ice. Overholser and Moses^{15*} found that temperature changes in cars being precooled by forced air circulation thru the bunker ice were greatly influenced by the amount of ice in the bunkers and by the size of the channels formed between the cakes of melting ice.

McKay^{14*} found that floor racks improved air circulation and caused more uniform refrigeration thruout the load. Winterrowd^{21*} stated it is highly desirable that there be no obstruction to the flow of cold air passing beneath the bulkhead and pointed out that splash boards, etc. may partially or entirely defeat the object of floor racks.

While studying air circulation in cars of unprecooled oranges one day after loading, MacFarland^{13*} found the air movement to be more

even, and in general faster, in cars with solid insulated bulkheads than in cars equipped with a type of open bulkhead. This was especially true of air moving from the bunkers to the top of the load at the middle of the car. Air movement averaged nearly twice as fast in cars with solid insulated bulkheads as in cars equipped with the open type. In studies in cars of precooled oranges eleven days after they were loaded he found the rate of movement above the load near the middle of the car to be 8 and 15 feet per minute in two cars equipped with open bulkheads as compared with velocities of 4 and 12 feet per minute at points similarly located in two cars with solid insulated bulkheads. The latter tests were made in the fall when heat absorption thru the walls was probably small. Since the fruit temperatures were low, the heat of respiration was relatively small. It would be expected therefore that air velocities would be extremely low.

Effect of Package Arrangement on Air Circulation

Lorion^{12*} stated that it is upon the longitudinal air channels that the load must depend for the necessary circulation of air. Sweeley^{20*} believed that best results are obtained when the air channels between the packages are unobstructed from the floor to the top of the load. Members of the Food Investigation Board^{3*} found, in studying air circulation in refrigerated ship holds, that more effective circulation could be obtained if some of the space given up to narrow horizontal channels were utilized in the formation of relatively large vertical channels.

The methods employed in loading refrigerator cars, particularly the longitudinal and vertical air channels left between the rows of packages, determine to a considerable degree the amount and extent of air circulation within the cars.

Winterrowd^{21*} claimed that to obtain the greatest advantage from air circulation the contents should be loaded so that the air can come in contact with a maximum surface with a minimum of restricted circulation. McKay^{14*} pointed out that the circulation of cold air from the ice bunkers thru the load by natural means is necessarily slow, and that if open spaces between the rows of packages are not provided, the flow of cold air toward the center of the car is checked. He stated that altho mixed loading is the most common cause of air blockades, careless loading or shifting of packages will bring about the same unfavorable conditions.

McKay found that cantaloupe crates loaded 4 high and 6 wide would not refrigerate properly, but that cooling was satisfactory in loads 3 high and 7 wide. This tends to corroborate Lorion's view^{12*}

that excessively wide air channels are not essential in refrigeration except as they reduce the size of the load. Hill, Graham, and Wright^{9*} found that heavy loading retarded air circulation within the car and thus prevented efficient refrigeration.

Ruddick^{18*} stated that provisions must be made for circulation of air thru the load, and that there should be a space left in the center of the car. He claimed that this gives good air circulation and even temperatures in the car. Lorion^{12*} disagreed with the idea that an open center load produces a chimney effect. He suggested instead that air movement at the center in such cases would be weak and that most of the movement would be upward thru the lading.

There seems to be little doubt as to the value of vertical and horizontal air channels thru the load, but the value of an open space at the center of the load seems to be uncertain. This may be related to the question of width of air channels thru the lading. In general it seems that the arrangement of packages has a very important effect on air circulation in the car and consequently on refrigeration of the lading.

EXPERIMENTAL METHODS AND PROCEDURE

Arrangements were made with the Illinois Central Railroad and with Illinois fruit shippers during 1929 for air-circulation studies in carloads of peaches and early apples. The work was planned so that an investigator could work in the car after it was loaded and during the first few hours it was in transit. Observations were made of the convection currents in carloads of fruit, and the velocities of these currents at certain points in the car were recorded. Whenever possible, temperature readings were taken at various points within the cars. Twelve electrical resistance thermometers that could be read from outside the cars were used for this purpose.

Cars Used.—Refrigerator cars used in the tests were taken directly out of active service. They were alike in design and construction, being insulated with the same type and quality of insulation and in all cases being equipped with box bunkers and solid insulated bulkheads. All cars used in the tests appeared to be in good condition, with tight-fitting doors and plugs and with no breaks in either the inside or outside of the floors, ceilings, and walls. Floor racks were present or absent as noted in the descriptions of individual cars.

Loading.—In most cases the usual commercial methods of loading were employed. Any variations from the normal practices are noted in the descriptions of the individual tests.

Tracing Air Movements.—In making some of the desired observa-

tions, more or less moving about over the load was necessary. Two 1-by-12-inch boards 32 inches long were used to protect the fruit in the top of the load against injury. The investigator remained on the boards, moving them about as necessary. At all times the boards were so placed that they would interfere with the normal air circulation as little as possible, considering the necessary activities of the person making the tests.

Titanium tetrachlorid fumes were used to trace the air movement within the cars. An apparatus patterned after one used by the United States Bureau of Mines was used as a smoke gun. It consisted of a long glass separating funnel filled with chunks of pumice stone. The stone was saturated with titanium tetrachlorid, and the ends of the tube were fitted loosely with plugs of glass wool. A rubber stopper containing a glass tube to which an aspirator bulb was attached was fastened in the open end. By squeezing the aspirator bulb, dense white fumes could be produced in any quantity desired, and with the use of heavy-walled rubber tubing the fumes could be delivered to any desired point in the

car. This arrangement proved very satisfactory for tracing air currents within the car and was used in all of the tests here reported. The details of design of the smoke gun are illustrated in Fig. 1.

As fumes were released in the car, the air movements were observed with an electric spotlight. Tracing the direction of the air currents proved to be a simple matter. The results of the observations were charted and described as they were obtained.

Problems in Measuring Air Velocities.—The accurate measurement of air velocities at various points in the cars proved to be a difficult

FIG. 1.—SMOKE GUN USED IN TRACING AIR CURRENTS IN REFRIGERATOR CARS

This instrument is capable of producing a dense white smoke in any quantity needed for tests such as described in this bulletin.

undertaking. The original attempts were made with Short and Mason anemometers. It was found that velocities at most points in the cars were not great enough to move the wheel of the anemometer at all, altho in a few locations readings were obtained. In such cases, however, the wheel of the instrument moved so irregularly that the readings obtained were discarded as worthless. A special slow-speed anemometer was used later in the season. It gave readings at much slower speeds than the other type. This instrument was so delicate in construction that it was not well adapted to use under the somewhat rough conditions which necessarily accompanied the studies in refrigerator cars. The difficulties of keeping the instrument properly calibrated made it unsatisfactory for the tests being conducted. The lower limit of its range was about 35 feet per minute, and the majority of air currents within the cars proved to have velocities below those accurately indicated by even this delicate instrument.

During 1929 attempts were made to measure the rates of movement in the space above the lading by timing the movement of smoke puffs liberated near the center of the car. The results were considered worthless because of the tendency of the smoke to spread and flow. Dandelion floats with the seeds removed proved to be much more satisfactory for that type of measurement. The figures obtained represented the average rate of movement over a considerable distance rather than the rate at a given point. Also the nature of this type of measurement naturally limited its use to uninterrupted spaces of considerable length.

Analysis of the results obtained in six cars of apples and peaches during 1929 disclosed considerable interesting information on the direction of air flow in refrigerator cars but no data of value as to the velocities of these air currents. It was evident that if any valuable data concerning air velocities were to be obtained, some instrument capable of accurately indicating very low air velocities must be found. It was also necessary that the instrument be fairly rugged in construction and that it require no bulky or complicated equipment for its operation. The hot-wire anemometer was considered, but the equipment necessary to operate it and the fragile nature of the recording wire discouraged its use. Fisher^{2*} reports that such an anemometer has been used successfully by the United States Department of Agriculture, and it may be that this instrument can be adapted successfully to work of this nature.

Use of Kata-Thermometer.—On the suggestion of Prof. A. C. Willard^a the kata-thermometer was tried in this work. This instru-

^aHead of Department of Mechanical Engineering, University of Illinois.

ment is essentially an alcohol thermometer with a large bulb. Its action as an anemometer is based on the variation in the rate of heat loss as influenced by the velocity of the surrounding atmosphere at any constant temperature. The thermometer and its use, as well as the physical principles governing its operation, are described in detail by Dr. Leonard Hill,^{7*} its inventor. Early tests showed it to be well suited to the investigations being undertaken. The kata-thermometer, together with all other equipment necessary for the work (thermos flask containing hot water, towel, stop watch, standard alcohol thermometer, electric lamp, smoke gun, and notebook) could be carried in a small hand-grip. The readings taken indicate the average velocity at a given point during a short period of time. Its accuracy at low velocities is much greater than that of any other portable instrument, the writers have found.

In this discussion of the accuracy of the kata-thermometer Hill stated that the observed cooling power of the air in millicalories per square centimeter per second (the quantity H/θ in the kata formula) cannot be taken as accurate within ± 2 percent of its calculated value. With that figure as a base the accuracies of the calculated air velocities have been plotted as shown in Fig. 2. It will be noted that the accuracy decreases rapidly as velocities fall below 15 feet per minute, especially

FIG. 2.—ACCURACY CURVE FOR THE KATA-THERMOMETER

The percentages within which the instrument is considered accurate at the velocities indicated are shown in this diagram.

for those below 10 feet per minute. It also seems probable that at velocities below 10 feet per minute slight convection currents may be set up by the heat of the warm kata bulb, thus further decreasing the accuracy of the readings. Therefore the writers consider that indicated velocities under 10 feet per minute show only that the rate of air movement was negligible at the time and place the readings were obtained. Probably velocity readings above that figure may be accepted as accurate within the limits indicated in Fig. 2.

The kata-thermometer has a further advantage in that it probably is a more accurate indicator of air movements that are somewhat irregular in velocity and direction than are instruments not based on the rate of cooling of a body by moving air currents. This characteristic is of importance in measuring the air movements in loaded refrigerator cars.

Because the kata-thermometer possessed so many advantages over any other instrument tested it was used for all air-velocity measurements that were made in refrigerator cars during 1930 and 1931.

Taking Velocity Readings.—During the early part of the investigations it was recognized that the body heat of the investigator and the effects of his breathing would tend to set up abnormal air currents within the cars. To reduce these effects as much as possible at the points where readings were being taken, the following precautions were observed during all of the tests here reported. The boards on which the investigator sat while taking readings were placed as far as possible to one side of the point where the readings were desired and so that they blocked a minimum number of air channels. Since smoke tests had shown that most of the air movement was longitudinal and vertical, it was believed that normal circulation would be least affected by the investigator working from that point. In order to reduce the effect of breathing, a large handkerchief was tied over the lower part of the operator's face. This tended to prevent interference with the normal air movement at the point where determinations were being made. Altho these precautions probably did not completely eliminate the abnormalities caused by the presence of the investigator, they undoubtedly did reduce them to a considerable extent.

Before readings were taken at any point the direction of movement was noted by using the smoke gun. All readings were taken with the long axis of the kata-thermometer held perpendicular to the indicated direction of air movement.

Air velocities at the upper bunker opening usually were taken at the middle section and at one of the extreme side sections of the opening. These sections are referred to in the text as the middle and the

FIG. 3.—UPPER BUNKER OPENINGS IN A REFRIGERATOR CAR

The openings in the cars used in the tests described in this bulletin were similar to those shown above.

side bunker openings. Fig. 3 shows the sections in the upper bunker opening of a standard refrigerator car. Load velocities, or the velocities with which air moved up thru the lading, were taken at average-sized openings between packages in the top layer unless otherwise specified.

GRAPHICAL METHOD OF PRESENTING DATA

The temperatures observed during the experiments are, for the most part, presented as charts showing the locations of isothermal lines in one half of the car at regular intervals, rather than in the conventional time-temperature graphs for each separate thermometer located in the load. This method apparently was used first by Lorion.^{12*} It is particularly advantageous because it gives a complete picture of conditions thruout the load without burdening the reader with a mass of detailed temperature data.

In making up the isothermal charts, the temperatures recorded in the bottom packages have been used as tho they applied to the bottom of the load outline and those in the top layer as tho they applied to the top line. Actually the points at which the fruit temperatures were taken were about 6 inches below the tops of the lids in all the packages. Therefore the true isotherms were slightly closer together horizontally than they are shown. If this fact is kept in mind, the charts presented give a clear and accurate picture of the temperature changes that took place within the cars during the most important part of the cooling.

In this method of presentation, temperatures taken in only one end of a car have been used. All these temperatures were taken in packages located in the middle rows which, in well-built refrigerator cars, are not noticeably affected by outside air temperatures. Data previously obtained by the writers^a indicate that the temperature conditions in opposite ends of the same car are very nearly identical, and that for practical purposes in uniform loads the conditions observed in one half of the car may be considered as prevailing in the other half.

For the purposes of this study the load has been considered as a unit rather than as being composed of a large number of separate units. It has been assumed that different positions within the packages will vary in temperature rather than that each basket will act as a unit showing a uniform temperature thruout but varying from those surrounding it. Altho there are few data available which bear on this point, it seems likely that most of the heat-transfer from the fruit within the baskets to the outside air is by conduction, and that under normal conditions convection currents within the packages are practically nonexistent. If this is true, the above assumption is justified and fruit in the upper part of a basket will be warmer than in the lower part of the same package. Further study of this point is necessary for a complete understanding of the cooling taking place in refrigerator cars.

TESTS WITH APPLES

In cars similarly constructed and equipped, in which all essential characteristics of the lading are alike, temperature conditions of both the fruit and the air tend to behave in the same manner. Temperatures at any given point in the lading of one car may differ slightly from those found at a comparable position in a similar car, but they tend to be equal and to maintain the same relative values in respect to temperatures at other points in the cars. Important trends and tendencies found in one car appear in all comparable carloads.

Car 1, a refrigerator car without floor racks, was loaded with 528 bushels of Yellow Transparent apples. The load was an end-to-end offset load 4 baskets high, 6 wide, and 22 long. About 200 baskets were loaded during the afternoon of the day before the test began. The rest were placed in the car before 3:40 p.m. the following day. The fourth row, which contained the thermometers, was placed at 10 a.m., and the first temperature readings were taken at 11:30 a.m. Temperatures observed in the car during the first 50 hours of the test are shown in Fig. 4.

When readings were first taken, fruit temperatures at the bottom

^aUnpublished data.

FIG. 4.—FRUIT AND AIR TEMPERATURES IN CAR 1, WITHOUT FLOOR RACKS

This car contained 528 bushels of apples loaded end-to-end 4 baskets high, 6 wide, and 22 long. Because of the absence of floor racks temperatures near the middle of the car dropped slowly.

of the load were somewhat higher than those in the top layer. This condition is not extremely unusual. Frequently the temperatures of different baskets will vary several degrees as they come from the packing shed, and it sometimes happens that the warmer fruit is placed

FIG. 5.—FRUIT AND AIR TEMPERATURES IN CAR 7, WITHOUT FLOOR RACKS

This car was also loaded with apples, as was Car 1. Temperature conditions were similar.

in the bottom layer. That condition was soon overcome in this car, and normal temperature relations appeared before 20 hours had passed. The time required for this would undoubtedly have been less had not the ice supply been rather low during that time.

Car 7 was similar in construction and equipment to Car 1. It was loaded with 528 bushels of Yellow Transparent apples. Two hundred

thirty bushels were placed in the car the afternoon before the first temperature readings were taken. The fourth row, in which the thermometers were placed, was loaded between 10:30 a.m. and 2:30 p.m. of the following day. Loading was completed at 3:30 p.m., and the first temperature reading was taken a few minutes later. Temperatures recorded in Car 7 during the test are shown in Fig. 5.

This load was rather uniform in temperature thruout, and the ice supply during the first 11 hours was much larger than in Car 1 during a similar period. Temperature conditions in Cars 1 and 7 therefore did not resemble each other very closely during the first 20 hours. After 30 hours the resemblance was very noticeable, and it became more so as the test progressed.

Temperature Differences Greater at Bunkers Than at Doors

An outstanding feature of the temperature conditions observed in both these cars is the wide differences existing between the fruit temperatures in the top and bottom layers at the bunker and the relatively small temperature differences existing between the fruit in these layers at the door. In both cars the temperatures of the fruit in the top layers tended to drop at about the same rate. This was particularly true in Car 7 in which there was never as much as 5 degrees difference between the temperatures at the door and at the bunker. The differences in Car 1 were a little greater than in Car 7, but the same general characteristics appeared in both cars.

Of particular interest in both cars is the wide temperature difference between fruit in the bottom layer near the bunker and in the same layer at the door. It is quite evident that during the first two days of these tests there was a very uneven distribution of refrigeration thru the bottom layer. Examination of the air temperatures (Figs. 4 and 5) shows clearly that the air reaching the bottom of the load at the door was relatively warm and therefore incapable of rapidly removing heat from the fruit.

The slope of the fruit isotherms in both these cars is very similar to that of the air isotherms at similar locations thruout the load. The fruit isotherms tend to lag from 7 to 10 degrees behind those of the air.

Air From Bottom of Bunker Returned to Top of Same Bunker

Air-circulation studies were made in both cars within six hours after the beginning of the tests. In Car 1 only the direction of air flow was observed, while in Car 7 the data on direction were supplemented with velocity readings at certain points within the car. The direction of air movement observed in the two cars was so similar that only the

data for Car 1 is reported here. Fig. 6 illustrates the paths followed by the air currents.

FIG. 6.—AIR CURRENTS OBSERVED IN CAR 1

Direction of air flow in both Cars 1 and 7 within six hours after the beginning of the tests suggested that there were two nearly independent circulating systems in the cars. While the cargoes were warm, air movement was more active near the bunker than at the door. Data for Car 7 were practically identical to those for Car 1.

While Car 1 was on the siding, smoke was liberated at the bottom of the lower bunker opening midway between the walls. It appeared above the load almost simultaneously at all points between the quarter-length and the door positions; practically none appeared between the quarter-length and the bunker. Most of the smoke appeared between the two middle rows and none appeared against the walls, indicating that there was relatively little lateral movement of air within the load. As soon as the smoke appeared above the load it moved toward the ceiling, at the same time moving toward the upper bunker opening.

After the above observation the hose thru which the smoke was delivered to the bottom of the load was drawn up about 8 inches so that it emptied at the top of the lower bunker opening. Smoke delivered at that position appeared between the bunker and the quarter-length but was seen first about 3 feet from the bulkhead. Thus the air issuing from the bottom of the lower bunker opening tended to remain near the floor, moving toward the middle of the car and upward as it was warmed, while the air coming from the upper part of the bunker opening tended to rise more rapidly and to possess a smaller horizontal component of motion.

Smoke liberated at the bottom of the load midway between the walls at the quarter-length position drifted upward and toward the middle of the car, at the same time diffusing laterally to a slight extent. Very little of it moved directly upward. Fumes liberated at the floor midway between the doors rose almost directly upward, tho they diffused somewhat in all directions. The smoke cloud divided as it ap-

proached the ceiling, part going to each bunker. It is interesting to note that when the fumes were released at the bottom bunker opening, nearly all the smoke returned to the bunker from which it came, even tho much of it appeared at the middle of the car. This suggests that there were two nearly independent circulating systems operating in the cars.

Direction and Rate of Air Movement Little Influenced by Movement of Car

Similar studies made while the car was in motion showed that the direction of air movement was not influenced to a noticeable extent by the movement of the car except that there seemed to be more lateral diffusion than when the car was standing. The car movement seemed to retard the rate of motion slightly, altho no air-velocity measurements were made and data subsequently obtained do not confirm this impression.

The movement of the car caused a vertical tossing or spring-like movement of the lading. The behavior of smoke released in the load suggested that some air was forced in and out of the baskets, but if it was, the movement was so slight that it must be classed merely as an

FIG. 7.—AIR VELOCITIES RECORDED IN CAR 7

The rate of air movement between the baskets was very slow at bunker, quarter-length, and door. The air currents entering the upper bunker opening were made up largely of air coming thru the load near the bunker.

impression rather than as an observed fact. Should it prove to be a fact that air is so forced in and out of the packages, it may account for the tendency for some loads to cool more rapidly while moving than when at rest.

As previously stated, the air currents observed in Car 7 were so nearly identical to those described above that repetition is unnecessary. The velocity determinations made in Car 7 are shown in Fig. 7.

The velocity of the air entering the upper bunker opening is of major importance because it is an index of the total amount of air circulating during a given unit of time. Thus it gives an indication of the rate of heat absorption by the ice at the time the reading is taken. The velocities recorded between the baskets at various points over the top of the load give an indication of the relative rate of air movement thru various sections of the load. It is important to notice in this car that the rate of movement between the baskets was very slow at bunker, quarter-length, and door, but particularly so at the latter position. In the light of the slow cooling rate at the door in all layers the weak air currents may be explained by the fact that air reaching the bottom of the load at that point was not much cooler than the fruit. It was therefore heated slowly, and the resulting upward movement was quite slow. As the fruit near the bunker cooled, air reaching the middle of the load should have been cooler and should have given rise to more active convection currents.

Car 2 was an iced refrigerator car equipped with floor racks. It was loaded with 280 bushels of Yellow Transparent apples the afternoon before temperature tests were begun. Loading was resumed the next morning and the thermometers were placed in the fourth row at 10:30 a.m. Loading was completed with 528 bushels in the car at 10:50 a.m., and the first reading was taken immediately thereafter. The temperature conditions recorded in Car 2 during the first two days of the test are shown in Fig. 8.

Air-circulation studies were made in the car while it was standing on the siding and while it was in motion. In this car smoke liberated below the floor racks at the lower bunker opening moved toward the middle of the load and upward, appearing at all points between the bunker and the middle of the car. Most of it appeared between the door and a point about 5 feet from the bunker. When smoke was released at the bottom bunker opening but *above* the floor rack, practically all of it appeared at the top between the bunker and the quarter-length position and most of it in the area within five feet of the bulkhead. It did not seem to move quite so rapidly as the smoke appearing farther out in the load.

FIG. 8.—FRUIT AND AIR TEMPERATURES IN CAR 2, EQUIPPED WITH FLOOR RACKS

The horizontal direction of the fruit isotherms in this car, loaded with 528 bushels of apples, is characteristic in carlots of fruit loaded on floor racks.

In general there seemed to be a more rapid upward movement of air near the middle of the load than near the bunkers. Above the load the most rapid air movement seemed to be between the bunker and the quarter-length position. The air movement near the roof at the middle of the car was very slow and took place in both directions. Much of

the smoke appearing at the top of the load between the doors moved diagonally upward and toward the bunker opening, leaving a somewhat stagnant area near the roof at the center of the car. Smoke liberated at the lower bunker opening against one side of the car diffused laterally as far as the line midway between the walls but did not pass it.

FIG. 9.—AIR CURRENTS OBSERVED IN CAR 2

As soon as air rose above the top layer of packages it usually moved directly toward the bunker opening. In general there seemed to be a more rapid movement of air near the middle of the load than near the bunkers. Results obtained while the car was in motion did not differ noticeably from those recorded while the car was standing.

Results obtained while the car was in motion did not differ noticeably from those recorded while the car was standing. The rate of movement did not seem to be affected seriously by the car motion, and the directions in which air currents moved were not altered. The same vertical tossing of the load observed in Car 1 was noticed in this car, and the impression that this increased air movement into and out of some of the packages was further confirmed. The directions in which the air currents were seen to move in Car 2 are shown in Fig. 9.

Car 6 was equipped with floor racks and was loaded with 528 bushels of Yellow Transparent apples. It was loaded at the same point as Cars 1, 2, and 7. Car 6, however, was loaded between 10 a.m. and 4 p.m. of the same day; thermometers were placed in the bottom layer

FIG. 10.—FRUIT AND AIR TEMPERATURES IN CAR 6, EQUIPPED WITH FLOOR RACKS

This car was loaded at the same point as Cars 1, 2, and 7 but between 10 a.m. and 4 p.m. of the same day. Fruit temperatures lagged several degrees behind the temperature of the air in most places in the car.

at 1:30 p.m. and in the top layer at 3:30 p.m. The first temperature reading was taken at 4:15, and air-circulation observations were made between 5:15 and 7:30 p.m. Temperatures observed during the first 50 hours are shown in Fig. 10.

FIG. 11.—AIR VELOCITIES RECORDED IN CAR 6

Velocities at selected points thru the load indicated active air movement thru the cargo at the doorway.

Velocity of Upward Air Movement Greatest at Middle of Load

The directions of air currents within the car were very similar to those in Car 2. There was the same general tendency for the upward currents to be stronger near the middle of the car than near the bunker. In Car 6 smoke was liberated successively above and below the floor racks at a point midway between the bunker and the quarter-length and at a point midway between the quarter-length and the middle of the car. The smoke liberated above the racks at both points moved vertically upward, diffusing to some extent as it rose, while that liberated under the racks moved toward the middle of the car and appeared above the load at all points between the point of release and the car doors. This indicates forcefully that the floor rack furnished a good supply of air to the middle portion of the load.

One of the interesting features of the air-velocity readings taken in Car 6 (Fig. 11) is the fact that the air movement upward thru the middle of the load was somewhat more rapid than at the quarter-length position and much more rapid than near the bunker. The fact that the air velocity 12 inches below the ceiling midway between the walls at the quarter-length was more than half that recorded at the middle bunker opening, suggests that a considerable proportion of the air moving into the upper bunker opening came from the middle section of the load.

Another feature of interest is that the air velocity thru the lading about 16 inches from the bulkhead was more rapid than directly against the bulkhead, indicating that there was a small section in which air circulation was not as active as in other parts of the car, and which, consequently, might be expected to cool more slowly. That section was small and apparently included only the baskets directly against the bulkhead.

Air Movement More Rapid Into Middle Bunker Than Into Side Opening

A third point of interest is the difference in the rate of air movement at the middle bunker opening and at the side opening. This seems to be a normal occurrence in most cars that are well supplied with ice, as this car was at the time the test was made. The bunkers were about four-fifths full at that time, and the side bunker openings were partly blocked with ice. As cars are iced, the space underneath the walk usually is not packed so solidly with ice as are the spaces directly below the plugs. This tends to allow freer air movement thru the middle bunker opening for some time after the car is iced. Thus air channels fed thru the middle bunker opening become better estab-

FIG. 12.—FRUIT AND AIR TEMPERATURES IN CAR 8, LOADED WITH BASKETS OF APPLES

Temperatures in baskets of hot fruit drop rapidly if the ice supply is sufficient to cool the air properly. This car was equipped with floor racks.

lished than those fed from the side. This does not necessarily mean that air velocities thru the lading will be more rapid near the line midway between the walls than they will be near the walls. As the ice supply decreases, the bunker openings are no longer blocked and velocities at the various openings tend to become more nearly equal.

Car 8 was equipped with floor racks and was loaded with 512 bushels of Duchess apples. It was loaded between 9:30 and 11:45 a.m. of the day the temperature readings were begun. The thermometers were put in place about 10:30 a.m., and the first set of readings was taken at 11:50 a.m. Temperature conditions observed in this car are shown in Fig. 12.

The load was a normal 22-by-6-by-4 end-to-end offset load, but 16 bushels were left out at one corner of the car. This space was braced with a frame of 2-by-4-inch lumber. It was left in the car so that some observations could be made of air velocities in the lower part of the load against the bunker. The thermometers were placed in the opposite end of the car, and velocity records at the upper bunker opening were taken at the opposite end so that the missing baskets would not interfere greatly with normal circulation and temperature changes.

Air-circulation observations were made between 5 and 8 p.m. The velocity readings obtained at various points within the car are shown diagrammatically in Fig. 13.

The directions taken by the air currents in the normal end of this car were similar to those observed in Cars 1 and 6, but the movement seemed to be a little more active than in those cars. This impression is borne out by the velocity data which show about the same rate of movement into the middle bunker opening in Cars 8 and 6 but a much more rapid movement into the side bunker opening of Car 8. The movement up thru the load near the bunker also was more rapid in Car 8 than in Car 6.

It is recognized that the absence of a part of the load against the bunker and the presence of the investigator in that space probably created somewhat abnormal conditions, especially in that end of the car. It seems likely, however, that the conditions approximated those that would have existed normally in that load.

Air Moved Horizontally Out of Bunker Opening

Smoke liberated at the lower bunker opening midway between the walls to determine the direction of flow at points where velocity readings were to be taken, showed a tendency for the air to move horizontally out of the bunker opening above, as well as below, the floor racks. Above the racks the smoke swung upward two to three feet away from the bunker but left a region of low velocity in the second layer of the bunker stack. This is shown by the air velocity of 13.2 feet per minute recorded in the second layer between the third and fourth rows and between the first and second baskets in the stacks. The velocity of 60.3 feet per minute recorded at the lower bunker

FIG. 13.—AIR CURRENTS OBSERVED IN CAR 8

Air movement out of the lower bunker openings in this car was found to be very active. The absence of a part of the load against the bunker and the presence of the investigator in that space probably created somewhat abnormal conditions, especially in that end of the car.

opening above the rack indicates very active air movement at that point, but the smoke tests showed that this movement slowed down considerably as the air came in contact with the lading.

Air under the racks moved out very rapidly toward the center of the car, but some of the smoke began to rise upward thru the rack within a foot or two of the point of release. This continued as far as the currents could be followed, and it seems likely that the velocity decreased continuously as the air under the racks approached the middle of the car. This is also indicated by the reading taken under the racks at the edge of the well opposite the bulkhead.

The temperature data presented in Figs. 10 and 12 indicate that the fruit loaded into Car 8 averaged nearly 15 degrees warmer than that in Car 6. Since the primary cause of the convection currents set up in refrigerator cars is the difference in temperature between the lading and the air issuing from the bottom of the bunker, it is to be expected that air velocities would be greater in Car 8 than in Car 6.

There is a similarity between the temperatures shown in Cars 8, 6, and 2, especially after the first 20 hours had elapsed and after the ice supplies in all three cars had been replenished.

Outstanding in all three cars with floor racks is the tendency for the fruit isotherms to move horizontally thru the load. The same tendency is seen to a lesser extent in the air isotherms. In the sixth chart of Fig. 10 the fruit temperature in the top layer of the bunker stack unaccountably remained stationary, thus drawing the isotherms out of horizontal. The fruit at that point showed an unusual lag behind the air temperature, and it seems likely that some unknown factor, such as a load shift at that point, brought about the observed condition. Aside from this one abnormality the cars all showed a decided uniformity of fruit and air temperatures over the top of the load and a less striking uniformity of fruit temperatures at the bottom. The air temperatures at the bottom of the loads in Cars 2 and 6 were fairly uniform, but in Car 8 the air temperature at the door was considerably higher than at the bunker. This may have been due to the fact that the test in Car 8 was conducted during unusually hot weather, and heat leakage thru the car floor may have raised the temperature of the air moving under the floor racks.

It will be noted that rather wide differences between the temperature of fruit on the bottom and top layers tended to appear during the first 20 to 30 hours, but that this difference tended to become smaller after about 40 hours except at the bunker in Car 6. This exception, as previously pointed out, was due to the abnormal temperature behavior of the fruit in the top layer of the bunker stack.

Floor Racks Tend to Equalize Temperatures and Circulation

Certain definite conclusions concerning the effects of floor racks may be drawn from the above data. Most noticeable is the tendency for floor racks to equalize fruit and air temperatures thruout the bottom layers of the load.

A comparison of the temperature data obtained in Cars 2, 6, and 8 with those taken in Cars 1 and 7 shows clearly that floor racks caused temperatures at the bottom layers near the door and toward the quarter-length to drop much faster than in cars not so equipped. In cars with floor racks the average temperatures of the lading dropped more rapidly during the first 50 hours than in cars without that equipment. This increase in the average rate of refrigeration was brought about almost entirely by more rapid cooling of the fruit in the middle half of the load. The fruit at and near the bunkers cooled equally well in cars with floor racks and in those without. It may therefore be concluded that the chief value of floor racks lies in their effect on the parts of the load which are some distance from the ice bunkers.

A comparison of the velocity readings obtained in Car 7, without racks, and those obtained in Car 6, equipped with racks, indicates that circulation in general was a little more active in the car with racks; the great difference between the two cars lay in the difference in air movement up thru the load near the middle of the car. The presence of floor racks caused air movement thru the load at that point to be over two and one-half times that observed in the car without floor racks.

The floor racks evidently furnished the middle of the car with a larger supply of air at a lower temperature, thus increasing the amount of refrigeration available in that section of the load. The effect of this increase in available refrigeration was to increase markedly the rate of cooling in the lower layers. As the air flowed past the fruit in the bottom of the load, it absorbed heat from those packages and so reached the upper layers somewhat warmer than it left the racks. This resulted in smaller temperature differences between the fruit and the surrounding air at the top of the load. Since the rate of heat exchange is a function of this temperature difference, the rate of cooling in the upper layers was necessarily slower than at the bottom of the load and the temperature difference between fruit in the top and bottom layers tended to increase. As the fruit in the lower layers cooled, the rate of heat exchange at those levels decreased and the air reached the upper layers at increasingly lower temperatures. This tended to maintain or in some cases to increase the rate of heat-transfer in the upper layers and to decrease the difference between the temperatures of the top and

bottom layers. This same phenomenon occurred near the bunker as well as in the regions near the door.

In cars without floor racks a somewhat different situation existed. Air that reached the bottom layer near the door had passed many warm baskets of fruit before it reached the center of the car. In doing so it had absorbed heat until when it reached the doors it was only a few degrees cooler than the fruit it was supposed to refrigerate. Heat-transfer was therefore slow from all layers between the doors. As a consequence of this slow heat-transfer wide temperature differences appeared between the fruit in the bottom layer against the bunker and that in the same layer at the door but not between the different layers in the middle of the car. The zone of rapid cooling therefore included only the lower layers near the bunker rather than embracing to a considerable extent all of the lower part of the cargo.

The rate of cooling in other sections of the load was limited by temperature differences between the air and the lading and by the amount of refrigeration available. Where these differences were small, the convection currents set up were weak, and satisfactory refrigeration was further delayed. As the fruit in the lower layers near the bulkhead approached the temperature of the surrounding air, less heat was exchanged there and the amount of available refrigeration at the more distant regions was increased.

The chief value of floor racks would seem to lie in their ability to supply cold air to the sections of the cargo near the doors rather than in the fact that they promote freer air circulation along the floor. It seems likely that the limiting factor in the rate of cooling at the middle of cars without floor racks is the temperature differences between air and fruit rather than the freedom of air movement along the floor. In so far as air circulation is concerned in cars without floor racks, the limiting factors probably are the ease with which air can circulate upward and the temperature differences inducing such circulation, rather than the ease with which air can move along the floor.

Better Refrigeration With Bushel Boxes Than With Baskets

Tests were made in two cars in which the fruit was packed in boxes rather than in baskets, to obtain some information concerning the effects of package shape on temperature conditions and air circulation in refrigerator cars.

Car 3 was equipped with floor racks but was loaded with 520 bushels of apples packed in corrugated paper bushel boxes.^a Between

^aThese boxes were used because they were more readily available than rectangular wooden boxes of that size.

FIG. 14.—FRUIT AND AIR TEMPERATURES IN CAR 3 LOADED WITH APPLES
PACKED IN CORRUGATED PAPER BUSHEL BOXES

Refrigeration immediately after loading was completed seemed to be more rapid in this car than in carloads of apples packed in bushel baskets. This car was equipped with floor racks.

9 a.m. and noon 240 bushels were loaded in the *B* end of the car. Fruit was loaded in the *A* end between 1:30 and 4:30 p.m. The thermometers were placed in the middle row of the *A* end. Boxes of the type used loaded nicely in stacks 6 wide and 4 high with longitudinal

and vertical air channels 3 to 4 inches wide between the rows. The load was stripped with building lath to prevent side shifting. Ten stacks were placed in the *B* end and 11 in the opposite end. Sixteen boxes were fitted in the remaining space to make a tight load. No air spaces were left in this middle stack.

The boxes were made of corrugated cardboard and were ventilated by 5 holes in each end and 7 in each of the two sides. Any effect which the end holes might otherwise have had was eliminated by the end-to-end method used in loading the boxes. The side holes may have allowed some air to enter the packages, but no definite information was obtained as to the amount of air movement thru the packed boxes as a result of these openings.

Temperature records were taken in the car during its trip to market (Fig. 14).

FIG. 15.—AIR CURRENTS OBSERVED IN CAR 3

With uninterrupted vertical and horizontal air channels thru the load, air moved toward the upper bunker opening as soon as it rose above the floor racks. Air movement observed in this car seemed much more rapid at all points than in Car 6, in which the equipment, lading, and fruit temperatures were similar to those in Car 3 but which differed in that the apples were packed in bushel baskets.

Between 5:45 and 7:45 p.m. air-circulation studies were made in the car both while it was standing and while it was rolling. The directions taken by the air currents observed are shown in Fig. 15.

Rapid Movement of Air Toward Upper Bunker Openings.—Smoke released at the middle of the lower bunker opening and above the floor racks moved almost directly upward at a moderate speed and remained within about 3 feet of the bulkhead. Fumes liberated at the same opening but under the floor racks moved very rapidly under the racks toward the middle of the car. Part of this smoke appeared above the floor racks within about 3 feet of the bulkhead and came thru the openings in the racks with considerable regularity between there and the middle of the car. The smoke liberated under the racks at the bunker diffused laterally to some extent, but most of it came up thru

the middle air channels. Almost all the smoke released above the racks moved upward thru the same air channel, altho small amounts did filter thru to the neighboring aisles.

As soon as the smoke appeared above the floor racks, it moved upward and toward the bunker. The drift toward the bunker was very definite, especially from points near the quarter-length position. Smoke released above the racks at that point moved in practically a straight line to the upper bunker opening. When liberated below the racks at that point it moved rapidly toward the center of the car but immediately began to appear above the racks. As soon as the fumes cleared the floor rack they moved directly toward the bunker opening. This tendency was most noticeable at the quarter-length position. At the middle of the car against the cross row of boxes there was some tendency for the currents to rise vertically, altho most of the smoke moved toward the bunker opening.

Practically identical results, it is interesting to note, were obtained in all the air passages, and the movement in the canals near the walls apparently was as active as in those midway between the sides of the car.

Air movement observed in this car seemed much more rapid at all points than in Car 6, in which the equipment, lading, and fruit temperatures were similar to those in Car 3 but which differed in that the apples were packed in bushel baskets. This was noticeable in the rate of movement under the rack, upward thru the load, and along the roof in the direction of the bunker openings.

Motion of the car seemed to have no appreciable effect on the direction of the air movement within the car. It did seem to retard the rate of movement to a very slight degree.

A comparison of the temperatures found in Car 3 (Fig. 14) with those for Car 6 (Fig. 10) shows that the rate of cooling on the whole was more rapid in Car 3 than in Car 6. This was especially true during the first 40 hours. After that the cooling in Car 6 was more rapid than in Car 3. After 50 hours had elapsed, the fruit temperatures in the two cars became very similar except for the abnormality previously noted in Car 6. When the tests had run 50 hours, the air temperatures in Car 3 were still somewhat lower than in Car 6, altho at the 40th hour this difference was less noticeable than later. It is difficult to formulate a satisfactory explanation of the fact that Car 6 cooled more rapidly than Car 3 after the 40th hour.

Uniformity of Cooling Due to Rapid Air Movement.—In general it seems that the effect of the boxes was to increase the rate of cooling over that in cars of baskets during the first 40 hours of the tests, to

FIG. 16.—LOADING PLACED IN CAR 14 DURING THE FIRST AND SECOND DAYS

The load in the B end of Car 14, containing apples packed in corrugated bushel boxes and equipped with floor racks, was 6 wide, 4 high, and 10 long. In the A end it was 7 wide, 4 high, and 10 long. Two bracing stacks in the center, to take up the extra space, were loaded solid with no air spaces between the boxes. Because of the unusual loading, temperatures recorded during the early hours of the test were not truly representative. (The crosshatched areas in the diagram above indicate the packages loaded during the first day.)

increase somewhat the uniformity of temperatures thruout the load, and to increase the rate of air circulation within the car during the first part of the trip. The increased cooling probably resulted from more available refrigeration at points thruout the load, which in turn was brought about by better air circulation. The greater uniformity of temperatures thruout the lading probably resulted from more rapid air movement. The temperature distribution and rate of cooling thruout the load suggest that the use of rectangular fruit packages might help to solve some of the cooling problems in refrigerator cars.

Car 14 was also loaded with apples packed in bushel boxes made of corrugated paper. It was equipped with floor racks. The load in the *B* end was 6 wide, 4 high, and 10 long, in the *A* end it was 7 wide, 4 high, and 10 long. Two bracing stacks were placed in the middle to take up the extra space. These two stacks were loaded solid with no air spaces between the boxes.

The test was run on fruit from a small packing shed with a capacity of about one car a day. The expectation was that the car would be loaded out in one day, but a high percentage of culls, together with

FIG. 17.—FRUIT TEMPERATURES IN THE *B* END OF CAR 14

The temperatures recorded in the *B* end of this car probably were not representative of temperature conditions there because of the influence of the stack at the door, which was one of the last stacks to be loaded.

difficulties met in handling the boxes, prevented this. About half the load was in the car at the end of the first day, and most of the remainder was loaded the following morning. Fig. 16 shows the part of the load placed in the car the first day and that placed the next. It also shows the location of the thermometers thruout the load. All thermometers were placed in the middle row.

It is readily seen from this diagram that the temperatures recorded in the *B* end probably were not representative of temperature conditions in that end of the car because of the influence of the stack at the door, which was one of the last stacks to be loaded. In the same manner the temperatures in the *A* end are not representative of the fruit in that end of the car because of the abnormal influence of the two bunker stacks, which were the only ones in that end to be loaded the night before. It is doubtful, therefore, if the temperatures recorded in this car (Figs. 17 and 18) can be taken as a true temperature index during the first part of the test. They became more representative as the test progressed.

Loading of this car was completed at 3 p.m. and the first tempera-

FIG. 18.—FRUIT TEMPERATURES IN THE *A* END OF CAR 14

The abnormal influence of the two bunker stacks, which were the only ones in that end to be loaded the night before, is evident in the temperatures shown here.

FIG. 19.—VELOCITY READINGS IN CAR 14 TAKEN SOON AFTER LOADING WAS COMPLETED

Readings for this car are incomplete because of an accident to some of the equipment. The most active air movement was in the end of the car containing the warmer fruit.

ture reading was taken at 3:25 p.m. Between 7:15 and 8:15 p.m. air-velocity^a readings were taken in certain parts of the car. An accident to the thermos bottle containing the water used for heating the katha-thermometer prevented the completion of the tests. The data obtained, however, are shown in Fig. 19.

The bunker velocity in the *A* end of the car was nearly twice that in the *B* end, indicating a much more active flow of air in that end. That condition probably resulted from higher fruit temperatures and from the greater quantity of fruit in the *A* end. The narrow air channels in that end evidently did not prevent active air movement thru the load. The few load velocities^b recorded do not seem to be very significant. It must be remembered that the load velocities against both bunkers were taken between boxes that had been in the car for over 24 hours and which, tho fairly warm themselves, were above fruit that had been cooled to a considerable extent. Under such circumstances slow air movement would be expected. The only velocity recorded in a warm section of the load was considerably greater than velocities at the bunkers.

Temperature Conditions Similar in Both Ends of Car.—Forty hours after the first velocity readings were taken a second set was obtained. At that time the ice supply had been replenished, and the thermometer readings were probably fairly representative of the average fruit temperatures in both ends of the car. Temperature conditions were very similar in the two ends altho slightly lower in the *B* end. Total circulation in the two ends was about the same (Fig. 20). The load velocities recorded indicate a more rapid movement in the *A* end, especially in the section from the quarter-length to the door. Since the air channels in the *B* end were somewhat wider than in the *A* end, the difference in total air movement was not so great as a comparison of the velocities would indicate.

A study of the temperature conditions prevailing in this car after 48 hours had elapsed indicates that the heavier load in the *A* end did not cool quite so satisfactorily as the smaller load in the other half, but the difference was not great. It seems probable that apples packed in the kind of boxes used in this test would refrigerate nearly as satisfactorily when loaded 7 wide as when loaded 6 wide. The air-circulation data, tho incomplete, suggest that air movement is influenced more by the difference in temperature between the air and the fruit than by the size of the air channels, provided the latter are large enough to permit free movement of air.

^aAir velocities refers to movements of air thruout the entire car.

^bLoad velocities refers to movements of air thru the load.

FIG. 20.—AIR VELOCITIES IN CAR 14 TWO DAYS AFTER LOADING

Air movement appeared to be equal in both ends of the car. The air-circulation data, tho incomplete, suggest that air movement is influenced more by the difference in temperature between the air and the fruit than by the size of the air channels, provided the latter are large enough to permit free movement of air.

Quantity of Ice Required to Maintain Refrigeration

In order to obtain some indication as to the amount of ice necessary to maintain refrigeration Car 14 was held on track without re-icing until the ice supply was nearly gone.

When the temperature readings were taken at the 94th hour of the test, fruit temperatures were still falling at all points except in the bottom layer against the bulkheads. At the 138th hour all the temperatures in the *B* end and half of those in the *A* end had begun to rise. Ten hours later only one thermometer failed to record an increase in fruit temperature. Somewhere between the 110th and 120th hours the temperature average reached its lowest point and the ice supply became insufficient to maintain existing temperatures (Figs. 17 and 18). At that time the bunkers were slightly less than one third full.

With higher fruit temperatures, with fruit that respire more actively than apples, or with higher outside temperatures more ice would have been required than was needed with this load to maintain existing temperatures. It seems likely that under ordinary circumstances adequate refrigeration will be maintained if the ice supply does not fall below half the bunker capacity of the car. In cars in which the lading is very warm it is possible that the reduction of the ice supply to half the bunker capacity might slow down the rate of cooling to some extent, but when the lading has been thoroly cooled, the ice supply can probably fall somewhat below half the bunker capacity without causing any significant increase in the temperature of the lading. These statements apply to cars whose bunker capacities are in the neighborhood of ten thousand pounds.

TESTS WITH PEACHES

During 1929 and 1931 tests were run in refrigerated carloads of peaches to determine the relation of air movement to temperature conditions in refrigerated loads. All cars used in these tests were equipped with floor racks and were in good condition as nearly as could be determined by careful inspection.

Car 4 carried 396 bushels of Elberta peaches loaded 3 layers high, 6 rows wide, and 22 stacks long in an end-to-end offset load.

The car was initially iced at 1 a.m. of the day the test began and was spotted for loading at 10 o'clock that morning. Between 2 and 6:40 p.m. 340 bushels were placed in the car. Thermometers were placed in the third row of the *A* end. That end was fully loaded by 6:40 and the *B* end of the load was completed except for 56 baskets which constituted part of the fifth and sixth rows. Probably refrigera-

FIG. 21.—FRUIT AND AIR TEMPERATURES IN CAR 4, LOADED WITH BUSHEL BASKETS OF PEACHES

This car contained a standard load of 396 bushels of Elberta peaches loaded 3 high, 6 wide, and 22 long by the end-to-end offset method and was equipped with floor racks.

tion in the *A* end during the night was little, if any, different from that normally occurring in fully loaded cars. Loading was completed at 9:30 the next morning, and shortly thereafter the car was hauled away to be re-iced. Air-circulation observations were begun in the car

a few minutes after loading was completed and were continued during the 4-mile trip to the icing station. The results of the temperature tests made in this car are shown in Fig. 21.

Air Currents Similar to Those in Apple Cars

Smoke tests showed the direction of the air currents to be similar to those found in cars of apples, but the movement thru the load seemed slightly more active than in apple cars. This may have been due to the fact that the smaller number of basket layers offered less resistance to upward air movement.

Smoke liberated at the middle bunker opening above the floor racks moved up thru the load at a fairly rapid rate but stayed within 2 or 3 feet of the bulkhead. When released under the floor racks, it moved under them toward the door, coming up thru the load rather evenly at all points between the door and a point about 3 feet from the bunker. As soon as the smoke cleared the top of the load it moved rapidly and in almost a direct line toward the upper bunker opening.

When released above the racks at the quarter-length, the smoke rose directly upward, diffusing slightly as it rose. When released under the racks at the quarter-length it appeared above the load at all points between the quarter-length and the middle of the car.

FIG. 22.—AIR CURRENTS IN CAR 4

The direction of the air currents was similar to those in cars of apples, but the movement thru the load seemed slightly more active.

The general rate of air movement seemed to be retarded slightly by the motion of the car. More of the smoke liberated at the middle of the car under the racks moved toward the rear bunker than to the head end while the car was in motion, but when the car was standing, it moved in about equal amounts to both ends. A defective or slightly loose plug might possibly have caused the movement toward the rear end as the car was in motion. The direction of the air currents observed in this test is shown in Fig. 22.

The foregoing test was made in 1929. During the 1931 peach season further studies were made in cars of peaches under standard refrigeration to determine more accurately than is shown by the results in Car 4 the air velocities that normally occur in cars of peaches.

Car 11 was iced early in the morning of the day the test began and was placed for loading about the middle of that morning. Loading was begun at 2 p.m. and completed at 5:30 p.m. The thermometers were placed in the fourth row between 3:40 and 3:50 p.m. and the car rolled at 6 o'clock. Temperature changes recorded in the car during the trip are shown in Fig. 23.

Air-circulation studies were made during the first 25 miles of the trip. Observations were made both while the car was in motion and while it was standing. During this same period velocity readings were taken in the rear end of the car (Fig. 24). All readings were taken while the car was in motion.

The direction of the air movement in Car 11 was practically the same as in Car 4. While the car was moving, some tendency was noticed for smoke liberated at the bottom of the load midway between the doors to move to the rear bunker in greater quantities than toward the bunker in the head end. This tendency was not apparent when the car was standing. These results agree with those obtained in Car 4 but not with some observations in carloads of apples. In Car 11 the smoke liberated at the middle of the lower bunker opening above the rack moved upward within about 5 feet of the bunker but appeared first and in greater quantities near the outer edge of this zone. The upward movement of the air currents 2 feet and less from the bulkhead was positive but seemed somewhat slower than at 3 to 5 feet from that end of the load.

A very active air movement into the bunker, especially at the middle, is indicated by the velocities at the upper bunker opening. These were higher than any recorded in cars of apples and greater than any subsequently recorded in cars of peaches. The velocities thru the load, at the same time, were moderate. This was especially true near the bunker. Apparently the low velocities near the bunker were

FIG. 23.—FRUIT AND AIR TEMPERATURES IN CAR 11, LOADED WITH PEACHES

Further studies were made in cars of peaches under standard refrigeration to determine more accurately than is shown by the results in Car 4 the air velocities that normally occur in cars of peaches.

in a zone of relatively slow air movement, the rapid air movement into the upper bunker opening and the consequent high rate of flow out at the lower opening probably producing a semistagnant region against the bulkhead.

FIG. 25.—AIR VELOCITIES RECORDED IN CAR 12

Car 12 was similar in most respects to Car 11. Air-circulation tests, however, were made during the two hours immediately following the completion of the load, and data were taken while the car was on a siding.

The rate of cooling of the lading in Car 11, while fairly rapid, was moderate as compared with that in Car 4 (Fig. 21). Altho no velocity readings were obtained in Car 4, the smoke tests seemed to indicate that velocities at the upper bunker opening were not so great as those in Car 11. The unusually rapid air movement at the upper bunker opening at the rear of Car 11 was due probably to the observed tendency of air rising thru the center of the load to go more to the rear bunker than to the head end while the car was in motion.

Car 12 was similar in most respects to Car 11. It was initially iced during the night and was placed for loading about 8:30 the next morning. Loading was begun about 9:30 and was completed at 3 o'clock that afternoon. The thermometers were placed in the third row at 11 a.m. Air-circulation tests were made during the two hours immediately following the completion of the load. All data of that nature were taken while the car was on the siding. The velocity records obtained are shown in Fig. 25. Temperature records taken thruout the load are illustrated in Fig. 26.

The air currents in this load appeared to be about normal, but they differed from those in Car 11 in that the smoke liberated in the lower bunker opening above the floor racks moved upward thru the zone near the bulkhead at a more uniform rate. This zone was not so large as in Car 11, being confined to the space within 3 feet of the bulkhead.

Air movement into the bunker was moderate (Fig. 25), indicating a reasonably good but not an unusual amount of circulation within the car. There was an exceptionally uniform movement of air thru the lading as a whole, with the movement near the bunker and near the middle of the load averaging a very little faster than at the quarter-length. This probably represents a more normal air movement for a warm car of fruit with a reasonably good ice supply than do the data obtained in Car 11. A reasonably rapid rate of cooling is indicated by the temperatures recorded in Car 12. Fruit temperatures showed less variation between the top and bottom layers in this car than in Car 11. The air isotherms were a little closer together in Car 11 than in Car 12 during most of the period shown in the charts, indicating slightly more uniform air temperatures thruout Car 12. In general, however, the two cars behaved very much alike, the outstanding difference between the loads being the greater uniformity of temperatures maintained in Car 12. The greater uniformity of air circulation thruout the load may have caused more even temperature drops in Car 12.

Car 13 was loaded with 396 bushels of Elberta peaches between 10 a.m. and 4 p.m. of the day on which temperature tests were first taken. Thermometers were placed in the fourth row of the load about

FIG. 26.—FRUIT AND AIR TEMPERATURES IN CAR 12

Fruit temperatures showed less variation between the top and bottom layers in this car than in Car 11. A greater uniformity of temperatures was maintained in Car 12, which may have been caused by a greater uniformity of air circulation thruout the load.

an hour before loading was finished. The first readings were taken at 4:30 p.m. The car was initially iced about 46 hours before loading began, and was re-iced 11 hours after it was fully loaded. The next morning it moved out to a northern market.

FIG. 27.—AIR-VELOCITY READINGS IN CAR 13

Air movement thru the load at the middle of Car 13, loaded with 396 bushels of peaches, was greater than at the quarter-length or near the bunkers. The air-circulation studies in this car were made several hours after loading was completed and after the lading had been partly cooled.

At 9:30 that morning, after the car had been hauled about 75 miles, an observer entered to study air circulation. The train was rolling continuously while the studies were being made, so all observations and readings taken represent conditions existing in a moving car.

Air currents in this car appeared similar to those in Car 11 except that smoke liberated at the bottom of the load between the doors divided about equally when it approached the roof, half going to each ice bunker. This would seem to indicate that the tendency for more air to go to the rear bunker than to the forward bunker while the car is in motion, as noted in Car 11, is not a normal characteristic of all carloads of peaches under refrigeration. The air velocities recorded at certain points are shown in Fig. 27. Velocities at the rear bunker opening and thru the load near that bunker were slightly greater than at comparable points in the front end of the car. This difference in air movement was not great enough to be noticed during the smoke tests, nor is it great enough to be significant.

Air movement thru the load at the middle of the car was greater than at the quarter-length or near the bunkers. This supports Lorion's view^{12*} that as the load cools, velocities near the center of the car tend to become relatively greater than near the bunker.

That both bunker velocities and load velocities were higher when the lading was warm than after refrigeration had been going on for several hours is shown by a comparison of the velocities in Car 13, taken about 20 hours after loading was completed, with those in Cars 12 and 11, taken soon after loading was completed. While the lower load velocities near the bunker in Car 11 appear to be an exception to this statement, the fact is, as has already been pointed out, that they were probably caused by abnormally high bunker velocities, producing a zone of semistagnant air next to the bulkhead. Air velocities in the car as a whole tended to decrease as the loads cooled, and load velocities tended to become relatively greater near the middle as the fruit temperatures near the bunker became lower than near the door.

Temperatures observed in Car 13 (Fig. 28) appear very similar to those in Car 11. Wider differences between the top and bottom layers seem to have prevailed much of the time in both Cars 11 and 13 than in Car 12. In all three cars differences in air temperatures decreased continuously and quite regularly. Differences in fruit temperatures were small at the outset in all the cars; they increased during the first 20 hours, and then decreased somewhat during the following 30 hours.

Forced Circulation Improved Refrigeration

The effects of forced air circulation on air movement within a car and on the temperature changes thruout the lading were studied during

FIG. 28.—FRUIT AND AIR TEMPERATURES IN CAR 13

Temperatures observed in Car 13 appear very similar to those in Car 11. In Cars 11, 12, and 13 differences in air temperatures decreased continuously and quite regularly. Differences in fruit temperatures were small at the outset in all three cars; they increased during the first 20 hours, and then decreased somewhat during the following 30 hours.

the 1929 peach season. Car 5, used for this test, was loaded between 3 and 4 p.m. with 387 bushels of Elberta peaches packed in tub bushels. The thermometers were placed in the third row between 3:20 and

3:30 p.m. Before loading began, two high-speed electric fans (Fig. 29) were mounted in the upper bunker openings so they forced air into the top of the bunker and out the bottom opening.

FIG. 29.—ELECTRIC FANS USED TO FORCE AIR CIRCULATION IN CAR 5

These fans were placed in the upper bunker openings to accelerate the normal air circulation. No velocity readings were obtained, but air movements appeared much more rapid than in cars without fans.

The fans were started at 4:30 p.m. immediately after the first temperature reading was taken but were stopped at 5:15 to permit switching the car. They were started again at 8 o'clock and ran continuously, except during re-icing, until 4:30 the following afternoon, when they were removed and the car was sealed. The bunkers were nearly full of ice when the test began, but required 4,800 pounds when re-iced at 9 o'clock the next morning. As soon as the fans were removed from the car it was iced again, 1,200 pounds being required to fill the bunkers to capacity. Since this practice is a form of precooling and is not a part of the standard refrigeration service, the cost of the additional ice used above that required for standard refrigeration should be borne by the shipper.

Circulation studies in the car were made a short time after the first re-icing. No velocity readings were obtained, but air movement appeared much greater than in cars without fans. Load velocities seemed highest next to the bunkers and appeared to decrease at points nearer the middle of the car. Smoke liberated at the lower bunker opening below the floor racks appeared from the quarter-length to the door

FIG. 30.—AIR VELOCITIES RECORDED IN CAR 10 WHILE FANS WERE IN OPERATION

This car was loaded with 528 bushels of apples and was fitted with the same fans used in Car 5. The load velocities averaged from two to three times as great as those in the peach and apple cars without fans.

but was seen first at the quarter-length. Smoke liberated at this opening but above the racks appeared first near the bunker and last near the quarter-length. There seemed to be little or no overlapping of these two zones. All of the smoke moved directly toward the fans as soon as it appeared above the load.

In connection with air-circulation studies in this car the velocity readings obtained in Car 10 (Fig. 30) are of interest. This car was loaded with 528 bushels of apples and was fitted with the same fans used in Car 5. The test was discontinued before significant temperature results had been obtained, but the velocity readings obtained while the fans were operating may well be compared with the air-circulation observations made in Car 5. The load velocities averaged from two to three times as great as those in the peach and apple cars without fans. They decreased as the distance from the bunker increased. This was similar to the tendency observed during the smoke tests in Car 5. It is probable that load velocities in Car 5 were greater than in Car 10 because there was less resistance to the movement of air up thru the lading.

Temperature records for Car 5 for the first 40 hours are shown in Fig. 31. The comparatively short duration of this period must be kept in mind when studying the rate of cooling and when comparing temperatures in Car 5 with those in other cars. It should also be remembered that the fans were operating during only two and one-quarter of the first five hours.

The outstanding characteristics of the cooling in this car are the uniformity of fruit temperatures thruout the load and the rapid cooling of the entire lading while the fans were in operation. The large number of air isotherms after 5 hours as compared with the small number at the 20th hour are also of interest. After 20 hours the entire load was much cooler and temperature differences between the air and the fruit became much smaller. Consequently less heat was thereafter transferred to the air, and there were smaller temperature differences between the air leaving the ice bunker and that reaching the top of the load at the door. After the fans were removed, the air temperatures rose at all points in the car except at the bunker opening. While they did not rise sufficiently to stop refrigeration within the car, the rate of cooling was very noticeably retarded.

A comparison of the temperatures in Car 5 with those in Cars 4 and 13 (those most comparable in initial fruit temperature) shows strikingly the uniformity of both fruit and air temperatures caused by forced air circulation. The increased circulation produced a much more even distribution of refrigeration thruout the cargo and increased

FIG. 31.—FRUIT AND AIR TEMPERATURES IN CAR 5

Temperature records for only the first 40 hours are shown. The outstanding characteristics of the cooling in this car are the uniformity of fruit temperatures thruout the load and the rapid cooling of the entire lading while the fans were in operation. Temperature gradients were much smaller in this car than in cars cooled by normal air circulation.

materially the average rate of fruit cooling. Both these phenomena are highly desirable in refrigerated carloads of perishables. The extent to which they appeared in Car 5 as compared with Cars 4 and 13 is an

indication of the value of circulating fans under circumstances such as prevailed in these cars.

The data obtained in Car 5 tend to substantiate Smith's calculations^{19*} that greater uniformity of temperatures thruout stacks of warm fruit is obtained by increasing the air circulation thru the stacks. In Car 5 a markedly greater drop in temperature also accompanied a large increase in the volume of air circulated during a given time. While increased air circulation in itself, according to Smith, has little effect on the average rate of cooling, this investigator has shown that acceleration in the rate of cooling is dependent on increases in the amount of refrigeration available per unit of time. Undoubtedly the greater air movement thru the bunkers of Car 5 caused faster melting of the ice, thus adding to the amount of available refrigeration. It may be concluded, therefore, that the improved cooling which accompanied the forced air circulation was caused by the more rapid melting of ice rather than by an increase in rate of air movement thru the load.

Both air movement and the rate of cooling of the fruit in refrigerated carloads of peaches, it would appear from the above tests, are greater when the fruit is warm than when the load has been under refrigeration for several hours. Increased air circulation, in turn, causes more uniform and more rapid cooling of the lading, the latter effect probably being caused more by the rapid melting of the ice and the consequent increase in available refrigeration, than by increased air movement past the fruit packages, as pointed out above. The motion of refrigerator cars in transit seemed, in some cases, to cause more air to move to the rear bunker than to the front of the car, but the results as a whole were too conflicting to be conclusive on that point.

TESTS WITH STRAWBERRIES

Air-circulation studies were made in five refrigerated carloads of strawberries packed in 24-quart ventilated crates, during 1930. All the cars used in the test appeared to be in good condition and were equipped with floor racks. Observations were made shortly after loading was completed.

Temperature readings are not available for any of these cars, and only a relatively small number of velocity readings were taken in some of them. It was impossible, as a rule, for the investigator to spend more than a short time in each car because loading was usually completed only a short time before the pick-up train arrived. When tests were made while cars were in motion, it was sometimes necessary to leave the train after a short trip. Certain interesting facts, however, are shown by these data.

Vertical Air Channels Stimulated Circulation

Car 15 was loaded in an unusual manner. The load was 8 rows wide instead of the usual 7. This left no air channels between the crates, the 8 rows of 24-quart folding ventilated crates occupying the entire width of the car. The crates were stripped with building lath. Sixteen stacks were placed in the car, leaving about 10 inches between the bracing gates. The stacks were three layers high but a partial

FIG. 32.—AIR VELOCITIES IN CAR 15, CLOSELY LOADED WITH CRATES OF STRAWBERRIES

Since the load in this car was 8 rows wide instead of the usual 7, no air channels were left between the crates, and air circulation was retarded. The bunkers were about two-thirds full of ice when the velocity readings were made.

fourth layer of 16 crates was placed in each end of the car, making a completed load of 416 crates. Results of the observation of air currents and velocity readings in the load are shown in Fig. 32. The bunkers were about two-thirds full of ice when these observations were made.

A fairly active upward air movement apparently took place in the space between the bracing gates. The smoke indicated that a considerable proportion of this air rose to the car roof, divided there, and flowed toward both bunkers. Some of the air moved horizontally above the load, rising slowly as it drifted toward the bunkers. The most active movement, however, appeared to be within 18 inches of the roof. A slight movement of air upward thru and between the

FIG. 33.—AIR VELOCITIES IN CAR 17, LOADED WITH STRAWBERRIES

The load of 420 crates was arranged in 7 rows, 4 layers, and 15 stacks. The air channels between the rows averaged 2 to 3 inches in width. Air movements thru the loaded part of this car were abnormally low, however, compared with those in Cars 15, 16, 19, and 20.

crates was noticed, but it was slow and lacked volume. Air circulation in the car as a whole was slow, judging from the velocity readings at the bunker. The fact that the velocity below the roof at the quarter-length was nearly half that at the bunker opening indicates that a large proportion of the air entering the bunkers came from the middle of the car and that relatively little air filtered thru the body of the load.

When air movement in this car is compared with that observed in cars of strawberries loaded 7 crates wide and 4 high, the effect of continuous horizontal and vertical air channels is apparent. The air movement in one such car (No. 17) is described below.

Car 17 was loaded with 420 crates of berries, the load being arranged with 7 rows, 4 layers, and 15 stacks. The air channels between the rows averaged 2 to 3 inches in width. At the time observations were made the ice bunkers were about three-fourths full. The air velocities recorded are shown in Fig. 33.

Air movement at the middle bunker opening was much greater in Car 17 than in Car 15, altho the movement at the side opening was more rapid in the latter car. Since the velocity at the middle bunker opening usually is somewhat more representative of the average flow than is the movement into the side opening, and since the average of these two readings was greater in Car 17, it appears that circulation, as a whole, was considerably more active in Car 17 than in Car 15.

The air velocity below the roof in Car 17 at the quarter-length was much less than in Car 15 and was well below the range at which the instrument is accurate. Apparently not much of the air entering the bunker in Car 17 came from the middle of the car. Smoke tests showed that the air movement between the bracing gates and above the load at the middle of the car was very sluggish. Most of the air moving thru the middle stacks came from the space between the bracing gates and moved diagonally upward and toward the bunker. This movement was very slow, as shown by the velocity records taken between the top and bottom layers of crates in that stack.

Tho air velocities thru the load were, on the whole, slow in cars of strawberries as compared with those in cars of apples and peaches, the total amounts of air moved during a given time may have been about the same because of the larger air channels in the strawberry loads. The load velocities in Car 17 were abnormally low, however, compared with those in the cars described below.

Open Centers Did Not Improve Circulation at Middle of Load

Car 16 was loaded with 7 stacks of strawberry crates in the *B* end and only 3 stacks in the *A* end. All air-velocity records (Fig. 34) were

FIG. 34.—AIR VELOCITIES IN CAR 16, CARRYING A SHORT LOAD OF STRAWBERRIES

This car was loaded with 7 stacks of strawberry crates in the *B* end and only 3 stacks in the *A* end. Air movement in the large space between the bracing gates was quite slow, but a considerable proportion of the air that rose from the floor eventually moved toward the bunker in the end of the car containing the full load.

FIG. 35.—AIR CURRENTS OBSERVED IN CAR 20 FOUR HOURS AFTER LOADING

Air velocities in this car were unusually high because the ice bunkers were nearly full and the side bunker openings were partly blocked with ice when the readings were taken. Air movement was much greater at the middle bunker opening than at the side.

taken in the *B* end. The ice bunkers were about half full at the time of the tests.

Car 16 showed about the same air movement at the middle bunker opening as did Car 17, but air moved into the side opening much more rapidly than in Car 17. Load velocities were somewhat faster at the quarter-length and bunker than in Car 17, but in both cars air movement between crates in the middle stack was negligible. The air velocity below the roof at the quarter-length was faster in Car 16 than in either of the other cars discussed, but the ratio of that velocity to the rate of flow at the middle bunker opening was no greater than in Car 15.

Air movement in Car 16 in the large space between the bracing gates was quite slow, but a considerable proportion of the air that rose from the floor eventually moved toward the bunker in the end of the car containing the full load. This probably accounts for the relatively high roof velocity at the quarter-length. The low velocities in the spaces between crates in the middle stack would not lead one to expect a relatively high velocity near the roof at the quarter-length position.

Air movement thru the load at the bunker and at the quarter-length in Car 16 while relatively slow was somewhat faster than in Car 17. The movement thru the stack at the bracing was negligible.

Readings in Car 20 (Fig. 35) were taken when the ice bunkers were nearly full and the side bunker openings were partly blocked with ice. The fruit when loaded into the car was quite warm, and as the car had been loaded for less than 4 hours when the readings were taken, the lading was relatively hot. Under such conditions air movement should be active, which it was. The unusually high velocity at the middle bunker opening shows that a large volume of air was entering the bunker during a given time. The relatively low velocity at the side opening reflected the influence of ice blocking the opening. An average of the readings at these two points indicates that there was a large amount of air circulation in the car as a whole.

The wide difference in velocities between the middle and side bunker openings was not reflected in the load velocities. Between the first and second rows of the second stack the air movement was about 50 percent greater than between the third and fourth rows in the bunker stack. Altho it is likely that most of this difference was due to the difference in these locations with respect to the bunker, differences in air flow at the upper bunker openings were not reflected to any great extent in the velocities between different rows in the body of the load.

It is interesting to compare the movement thru the top layer of the

FIG. 36.—AIR-VELOCITY READINGS IN CAR 19 WHEN STANDING AND WHEN MOVING. Movement of the car had no effect on the rate of air movement into the bunker and thru the load.

second stack from the bracing in this car with velocities between crates in the bracing stacks in Cars 16 and 17. The noticeably greater air movement thru the second stack from the bracing in Car 20 may indicate that the open space between the bracing tended to retard rather than to increase air movement. Such a theory is borne out by the relatively active air movement at the middle of basket loads that have no open spaces between the two halves of the cargo.

The theory that air rises mostly between the rows of warm fruit rather than thru the openings between the middle stacks is further substantiated by the data obtained at the bracing in Car 19 (Fig 36). The velocity between crates in the top layer of the bracing stack indicated practically no movement at that point, but air moving between the crates in the bottom layer of that stack and drifting farther into the load as it rose, showed a moderately good velocity.

In Car 19 the upward movement of air between the bracing gates was very slow and somewhat irregular. Some air movement into the bracing stack was apparent at all layers, but it was most pronounced at the bottom layer and least so at the top layer. The air tended to move upward and toward the bunkers as soon as it rose above the floor racks (Fig. 37). These data tend to substantiate Lorion's opinion^{12*}

FIG. 37.—AIR CURRENTS IN CAR 19

Air moved thru this load in the general direction of the upper bunker openings as soon as it rose above the floor racks. The data shown here tend to support the opinion that in cars with open center loads most of the air moves upward thru the lading rather than thru the open center.

that in cars with open center loads most of the air moves upward thru the lading rather than thru the open center.

Circulation Not Affected by Car Movement

Results obtained in Car 19 are of particular interest because they indicate that movement of the car had no effect on the rate of air movement into the bunker and thru the load. All readings taken while the car was in motion were taken only after the train had attained a rather high speed. The velocity of the air entering the middle bunker opening was the same whether the car was moving or standing. This also was true of the air movement upward thru the bunker stack. These results are of interest in connection with those obtained in carloads of peaches.

Air movement is as active in most strawberry cars as in carloads of peaches and apples, judging from velocity readings at the bunker openings. Air velocities up thru the load were, on the whole, greater in apple and peach cars than in loads of strawberries, but because of unlike air channels in the different types of loads probably as much air moves thru the lading in carloads of berries as thru loads of peaches or apples. Some longitudinal and vertical air channels apparently are necessary for proper air circulation in strawberry loads. In general it seems that open centers have no beneficial effects on air circulation, and that air movement thru the bracing stacks is slower than thru stacks somewhat removed from the open center. Air movement thru the bunker stacks was not so rapid as thru the stacks some distance from the bulkhead.

SUMMARY AND CONCLUSIONS

1. Data showing air circulation and temperatures observed in 18 carloads of apples, peaches, and strawberries shipped under various conditions are presented and discussed.

2. Cars without floor racks, when loaded with bushel baskets of apples, developed large temperature gradients in the bottom layers and large vertical gradients near the bunkers. Temperature gradients were small in the top layers of such cars and in the stacks near the middle of the cars.

3. Cars of apples loaded on floor racks showed large vertical temperature gradients in all stacks and relatively small horizontal gradients in all layers.

4. Average temperature drops were more rapid in cars equipped with floor racks than in cars without that equipment.

5. Air circulation appeared more active in cars with floor racks than in those without them. The greatest difference in circulation appeared in the upward movement of air thru sections of the lading near the doors.

6. The chief value of floor racks appeared to lie in their ability to supply cold air to the sections of the cargo near the doors rather than in the promotion of free circulation along the floor.

7. Refrigeration was more rapid and more uniform in a carload of apples packed in bushel boxes than in comparable cars of apples packed in bushel baskets. The smaller temperature gradients were probably the direct result of the more rapid air movement. The increased cooling may also be traced back to the more rapid air movement, the increased air circulation thru the bunkers causing more rapid melting of the ice and consequently a larger amount of available refrigeration.

8. Data obtained indicate that in well-built refrigerator cars, when the lading has been thoroly cooled, the ice supply can fall well below half the maximum capacity of the bunkers without allowing an increase in fruit temperatures. This statement applies to cars with ice bunkers of about ten thousand pounds capacity. The size and character of the lading, as well as its temperature, undoubtedly will influence the extent to which the ice supply can be depleted without causing temperature increases in the load.

9. Forced air circulation in a carload of peaches materially increased the rate of cooling of the fruit and decreased temperature gradients thruout the load.

10. In carloads of peaches and apples both air movement and the rate of cooling of fruit were greater when the lading was warm than after it had been cooled for several hours.

11. Data concerning the effects of motion of a refrigerator car on air circulation within indicate that such motion does not necessarily affect the convection currents within the car. In two carloads of peaches the air movement appeared to be affected, but it seems likely that the observed influence was due primarily to some other factor such as a slightly loose bunker plug or an open drain trap.

12. Air movement thru the load as a whole in strawberry cars appeared as active as in carloads of peaches and apples, but load velocities, or movements of air thru the load, were lower in berry cars, probably because of larger air channels.

13. Longitudinal and vertical air channels appeared to be necessary for maximum circulation in carloads of strawberries.

14. Open centers in carloads of strawberries had no beneficial effects on air circulation and seemed to retard air movement thru the

bracing stacks. This suggests that carloads of American 24-quart strawberry crates might well be loaded 16 stacks long instead of 15, but it must not be construed to mean that proper bracing of the load can be neglected.

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