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ENGINEERING BETTER INTERFACING OF THE LOAD, THE TRANSPORT VEHICLE, AND THE REFRIGERATION UNIT FOR IMPROVED TRANSPORTATION

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Abstract. **Recent developments in transportation, refrigeration, and citrus-handling technology, together with the spiraling costs of fuel, labor, and transportation, have created both problems and opportunities in the transportation of the products to both domestic and foreign markets. Correction of the problems requires that the best transport and handling environments possible be provided for adequate protection of the inherent quality and condition of the fruit and, that, at the same time, transportation and distribution costs be held down. Such objectives often appear to be mutually exclusive, but need not be so. One way in which both objectives can be achieved effectively is through an improved interfacing of the load mass with the refrigeration system of the transport vehicle. Benefits to be gained through the application of this technology include: (1) More rapid and uniform cooling of the loads and, consequently, reduced quality loss and extended shelf life; (2) increased densities and, therefore, greater load stability, both of which will enhance unitized and palletized loading and transport and help to reduce package and product damage; (3) improved utilization of vehicle-cube, resulting in reduced transport and handling cost per unit of fruit; and (4) an increase in the versatility of the vehicles in that they can be fitted for use of cryogenic precooling and for more effective fumigation of the loads. Much progress toward the attainment of these goals within the constraints imposed by the transport systems in which the vehicles are used has been made in research and engineering by the U.S. Department of Agriculture (USDA) in cooperation with various industry cooperators. The systems approach used in this work involved functional engineering in which new design parameters were used that were based upon performance data obtained in stationary testing and in shipping experiments with various perishable products, including citrus, in both single-mode and multimodal transport.**

The Problems and the Challenges in Transporting Citrus

The providing of optimum temp for various citrus fruits during transportation is a vital and necessary step in the protection of inherent product quality and shelf life and in the prevention of spoilage during marketing. The optimum temp for this purpose differ with the type and variety of fruit, growing area, season of the year, condition of the fruit, and various other factors. For example, the optimum temp for grapefruit during transportation vary from 10° to 15.6°C (50° to 60°F), depending upon the time of year, where the fruit is grown, and under what conditions it has been stored before shipment (6). Optimum temp for the transport of oranges also vary with the variety, growing area, and preshipment storage temp. For oranges grown in the Arizona desert, for example, the optimum temp is 9.7°C (48°F) for oranges harvested in March and 3.3°C (38°F) for oranges harvested in June. The optimum temp for maximum protection of the shelf life of California 'Valencias' are from 5° to 6.7°C (41° to 44°F), whereas, for Florida 'Valencias,' the optimum temp is 0°C (32°F). The longer the distance the fruit is shipped to market, the more critical is the need for adequate temp control during the transit period.

In recent years the cost of providing refrigeration for fruits during transport has risen considerably. Refrigeration is energy intensive, and the cost of energy has increased substantially; in some instances, severalfold. The labor inputs and material costs for the repair and servicing of transport refrigeration units also have increased, in both land and sea transport. Per-unit, or per-vehicle, refrigeration costs vary directly (although not necessarily proportionately) with the distances the shipments move. Therefore, long-distance shipments of fruit have been adversely affected to a much greater extent than shipments which travel only comparatively short distances.

Transport refrigeration and freight charges for perishable shipments by railroad and by truck in the United States and for shipments by van container to overseas markets are generally on a per-vehicle basis. Therefore, the greater the number of boxes of fruit shipped in each vehicle, the lower the refrigeration cost per box. This same relationship also generally holds true for freight charges, and, therefore, for the freight costs per box of fruit.

One of the distinguishing characteristics of conventional air circulation systems in most refrigerated railcars, trucks, and van containers is that open stowage patterns are necessary so that cooled air can penetrate the load mass and remove heat from the fruit. Such open stowage patterns reduce load density, resulting in lower utilization of available loading cube and higher refrigeration and freight costs per box of fruit than when tight stowage patterns are used. Open stowage also introduces instability into the load mass, thereby predisposing it to shifting and disarrangement that frequently results in shipping container and product damage. Therefore, the adequate cooling of the fruit during transit and the achievement of high load density for the optimization of transport and refrigeration costs apparently are incompatible objectives. These goals are particularly incompatible for most refrigerated transport vehicles in which the cooled air is discharged over the top of the load mass. Research by personnel of the Agricultural Research Service and the refrigerated transport industry has shown that the over-the-load discharge of cooled air is one of the poorest methods for the interfacing of the refrigeration system in the transport vehicle with the load mass for transport of fresh fruits and vegetables. However, it has given acceptable performance for the transport of frozen foods, which require cooling only around the periphery of the load mass.

For the citrus industry to exploit distant markets for its fruit, transportation costs for the fruit must be held to a practical minimum. Such exploitation also requires that the fruit reach the markets in good quality and condition and with sufficient remaining shelf life to allow it to survive subsequent physical distribution steps. The challenge the citrus industry faces in shipping its fruit to distant markets is the accomplishment of both of these goals simultaneously. One way that shippers can accomplish both goals simultaneously is by use of the improved methods of interfacing the load mass of the fruit with the refrigeration units in the transport vehicles.

The Refrigeration System in the Transport Vehicle

The cooling of most shipments of citrus fruit requires that both vital heat and sensible heat be removed from the fruit as quickly as possible after it is loaded into the transport vehicle and that the temp be maintained as close to the optimum as possible during the entire transit period. Since much citrus fruit is not precooled before shipment (pretransit cooling), the removal of the initial ("field") heat from the fruit in the transit vehicle, including heat absorbed in drying and other preshipment processing, imposes a heavy cooling burden on the refrigeration system in the vehicle. Such removal can be accomplished only if the refrigeration unit has sufficient cooling capacity and if the whole system functions effectively so that the cooling capacity can be applied effectively to removal of the heat from the load.

Since the refrigeration system consists of the refrigeration unit and the heat transfer medium, which is the circulating air that must penetrate the load mass, the refrigeration system must, of necessity, include those parts of the transport vehicle that are related to air circulation, such as the blowers, the air plenums, and the load mass, itself. Also, since the load-mass characteristics determine the extent to which the circulating cooled air in the vehicle can penetrate the mass for heat removal, they become vital factors in the cooling equation. These characteristics include the shipping containers as well as the stowage patterns used for them. Efficient performance for the most effective use of system capacity, therefore, requires that all parts of the system interface in the most effective way possible.

Interfacing the Refrigeration System With the Load in the Transport Vehicle

Rapid and uniform cooling of all the fruit in a load can be accomplished only if an adequate volume of the circulating cooled air can penetrate the load mass, move through all its parts, and return to the cooling source (usually the evaporator coils of the refrigeration unit). The accomplishment of such rapid and uniform cooling requires that the best possible use be made of differentials in the static pressures in the air circulation system.

Research by Goddard (3) with simulated loads in stationary tests showed that pressure differentials can be used most effectively through delivery of the cooled air to 1 of 6 faces of the six-sided load mass at sufficient static head pressure and through application of the system suction, or negative pressure, to the opposite face of the load mass. At the same time, the cooled air must be prevented from going around the remaining four sides of the load mass and, thereby, bypassing the load mass.

Recent research by Goddard (2, 3) has indicated that the most practical and effective area for the interface between load mass and the circulating cooled air is the bottom, or under face, of the load mass. As Goddard (2) pointed out, the configuration of the bottom, or under face, of the load varies less than the configuration of any of the other faces in the transport of different products in different types and sizes of shipping containers. Also, when the bottom face of the load is the area of interface, shipping containers can be loaded tightly against the side and end walls of the transportation vehicle and, thereby, prevent excessive bypassing of the circulating air around the periphery of the load. Under such conditions, pressurization of the bottom face of the load mass, combined with the application of suction, or negative, pressure to the top face of the load, will force cooled air to move upward through the load.

Importance of Shipping Containers

A key element in the interfacing of a load with the air circulation system is the shipping container. For the rapid removal of heat from fruit, some of the circulating air moving through the load mass must also pass through the shipping containers (7). In many loads, the cooled air cannot enter the containers because the vent openings on the side and end panels of the boxes are partly or completely blocked by tight contact between the sides and ends of adjacent containers. Under such conditions fruit in the shipping containers cool largely by conduction of heat through the container walls. Consequently, cooling is extremely slow.

When corrugated fiberboard boxes are used as shipping containers, cooling by conduction can be retarded severely because of the natural insulating characteristics of the fiberboard. Also, when cooling occurs under such conditions, some moisture usually migrates from the product to the air inside the boxes, and thence, to the boxes (2). When the temp of the fiberboard reaches the dew point of the air inside the box, part of the moisture in the air condenses on the inside surface of the box and is absorbed by the fiberboard. Such moisture absorption by untreated corrugated fiberboard may weaken it significantly and thus reduce the ability of the box to bear much overhead weight without crushing or creasing. Such moisture migration is not as much of a problem with most citrus fruits as it is with products that have higher rates of respiration, such as some fresh vegetables.

The vent openings on most corrugated fiberboard boxes used for citrus fruit in the United States are on the side and end panels of the boxes. With that design, the cooled air cannot effectively remove heat from the fruit in any refrigeration system in which the air must move vertically, either up or down, through the load mass. Therefore, when vent openings are located on the tops and bottoms of corrugated fiberboard boxes, circulating air can enter and pass through the boxes (7). Wirebound boxes, because of the open spaces between the slats, are suited ideally to vertical-air-circulation systems.

Effects of Palletizing and Unitizing Shipping Containers

It might appear that palletizing and unitizing shipping containers would enhance the effectiveness of vertical air circulation systems, especially when the cooled air is delivered to the bottom face of the load mass. However, much depends upon the direction of the air circulation under the load and the type of unitizing devices used for the shipment.

If the stringers of two-way entry pallets should be placed at a right angle to the path of the circulating air as it is introduced under the load, lateral airflow could be seriously inhibited. Platform pallets also can interfere somewhat with the vertical movement of air through the load if the spaces between the deckboards are not wide enough, and if the spaces are too few, resulting in complete or partial blockage of the vent openings in the bottoms of boxes in the bottom layer. The air-circulation problem is even worse when conventional slipsheets without vent holes are used for unitizing the loads. Of course, insufficient circulation can be readily remedied by having sufficient vent openings in the slipsheets. Since practically all slipsheets now in use are solid or corrugated fiberboard, the incorporation of a large number of vent holes of sufficient size in the sheets may weaken them seriously or predispose them to tearing easily during use. Strengthening of the slipsheets or the use of plastic pull sheets with vent openings molded into them might avoid the tearing problem.

Importance of the Air Delivery System in a Transport Vehicle

The most vital element in the interfacing of load mass with a transport vehicle's refrigeration unit is the delivery of the cooled air to the load mass. In conventional air circulation systems, such delivery is usually by 1 of 2 methods. In one method, the air is delivered through fabric ducts that are attached to the ceilings in most refrigerated trailers or van containers. In the other method, the air is delivered through plenums enclosed in the ceiling of the vehicles. The latter method is used in most mechanically refrigerated railroad cars in the United States and in some refrigerated van containers.

Original thinking was that the cooled air discharged from ceiling air ducts in conventional air circulation systems settled downward uniformly through the load mass and then returned along the floor channels under the load to the return air inlet in the bottom of the forward bulkhead. However, Hinds and Chace (5) found that much of the air discharged onto the top of loads of citrus fruit in refrigerated trailers did not move through the load mass. As the cooling air left the ceiling ducts, it abruptly changed direction and moved over the top of the load toward the front of the vehicle. It was then drawn downward along the sidewalls in the forward third of the vehicle to the return inlet in the bottom of the bulkhead. They also observed that the abrupt change in direction of airflow toward the front of the trailer produced an aspiration effect at the rear of the load. This aspiration pulled the air upward along the sidewalls in the rear third of the trailer. Under such conditions little of the cooled air penetrated the load, and fruit cooling was retarded.

Delivery of the cooled air to the bottom face of the load mass could be from either the front or the rear end and from either one or both sides. Practically all bottom air-delivery systems in use in a small, but growing, number of refrigerated van containers are from the front, and the channels between ribs in the "T"-type aluminum alloy floor form the delivery channels. Systems that deliver air longitudinally from one end are also used in a few railroad mechanical-refrigerator cars in the United States.

The principal deficiency in the longitudinal air-delivery systems is that obtaining and maintaining adequate system pressure on the bottom face of the load is difficult. In refrigerator cars in which the circulating air is delivered to the bottom face of the load through the space of 92.2 mm (3 5/8 inch) between the bottom of the floor racks and the car floor, the difficulty is particularly severe.

A lateral, under-the-load air delivery system is used in an experimental refrigerated van container developed by the USDA. So far as is known, it is the only one of its type in existence. In this container the air supply is delivered to the bottom face of the load, from air plenums in both sidewalls, through crosswise channels in the aluminum alloy floor. The channels are 12.7 mm (1/2 inch) wide and 19.05 mm (3/4 inch) deep. In addition, because the interior sidewall surfaces are flush, the shipping containers in the load can be fitted tightly against the sidewalls so that the prevention of air leakage around the sides of the load mass can be facilitated. Because of these 2 features—the flush sidewalls and air delivery to the bottom of the load—the bottom face of the load can be pressurized by air delivered from the sidewall air plenums.

The cooled air supply from the refrigeration unit is delivered to the sidewall air plenums by 2 totally enclosed ceiling air ducts, one on each side of the ceiling. Both ducts are 0.15 m (6 inches) deep and are tapered laterally from 0.61 m (2 ft) wide at the front to 0.25 m (10 inches) at the rear. The ducts, which extend the full length of the container, are attached to the front bulkhead where they interface directly with the air discharge outlet from the refrigeration unit. The cooled air supply from the refrigeration unit is, therefore, discharged into the sidewall air plenums through the ceiling ducts in uniform quantities and at comparatively uniform pressures.

These features of the experimental container's air distribution system permit delivery of the supply of cooled air to the bottom face of the load with a high degree of uniformity, in both volume and pressure. Since the air supply is delivered from openings along both sidewalls to the bottom face of the load, the system is pressurized throughout the whole length and width of the cargo area. With the suction, or negative pressure, on the top face of the load, the condition is created for a steady, uniform, upward movement of cooled air through the load mass.

In terms of both the cooling and the heating of the load as may be required at any time in transit, both systems for the interfacing of air supply with the bottom face of the load have several important advantages over the conventional over-the-load discharge system. Melby (8) pointed out that one important advantage of an under-the-load air-delivery system was that the vehicle floor and the structural members would serve as a heat sink and thereby provide a refrigeration reserve when the refrigeration unit was not operating. Also, circulating the air under the load will help prevent product freezing at the point in the vehicle where it would be most likely if ambient temp should fall considerably below freezing.

There also is an additional advantage in interfacing the air delivery system with the bottom of the load mass in such a way that the system can be pressurized to force the air through the load that relates specifically to the distribution of citrus fruit. With this type of air circulation system, it is a relatively simple matter to adapt trailers or van containers to allow for introduction of fumigants into the air for circulation through all parts of the load.

Importance of Pressures in Air Circulation Systems

As has been indicated in the foregoing section, the way in which the air supply system is interfaced with the bottom of the load determines whether sufficient static pressure can be maintained at the interface for circulation of air through the load. Guillou (4) showed the importance of static head pressures in maintaining the flow of sufficient cooled air to fresh grapes to shorten precooling times. He also emphasized the importance of interfacing the masses of fruit to be cooled with the cooled air supply in room precoolers. The pressure differential between the opposite faces of the load is the factor that causes air to move through the load. If conditions are provided such that the cool air moving through a load can pass through the individual boxes, instead of around them, the cooling rates for the fruit will be greatly enhanced.

The static head pressure at which the cool air supply is delivered to the bottom face of the load mass in the USDA experimental van was reported by Goddard (2) to be 373 pascals (1.5 inches of water). The air supply is provided by 2 air blowers, one at the inlet to each ceiling duct. The blowers are rated at about 708,000 cm^3/sec (1,500 ft^3/min) at an available discharge presure of about

547 pascals (2.2 inches of water). The loss in system pressure between the blower outlets and the bottom of the sidewall air plenum is about 124.5 pascals (0.5 inch of water).

These static head pressures contrast sharply with those in most conventional refrigeration systems in trailers, van containers, and rail refrigerator cars, in which the cooled air is discharged over the load. Goddard (2) reported that measurements of static pressure at the point where high-capacity, over-the-load fans discharged air into the ceiling ducts averaged about 124.5 pascals (0.5 inch of water). Readings taken at various points in the space between the top of the loads and the ceilings of trailers and van containers in which such conventional systems have been used have revealed no measurable static head pressures.

The pressure differential through a load mass varies, of course, with the density of load, including the tightness of load stacking and the tightness of product packing in the shipping container. However, with light-density products, the pressure differential through the load in the USDA van container was 12.5 pascals (0.1 inch of water). Because of the unevenness with which the suction, or negative pressure, is applied to load mass in the conventional, over-the-load air discharge systems, the through-the-load pressure differential could range from 0 to as much as 124.5 pascals (0.5 inch of water) from the rear to the front of the load, depending upon the capacity of the refrigeration unit's air blower. This variation in the range of system pressures would result in a wide range in air velocities throughout the load, as noted by Hinds and Chace (5) in the measurements of rates of air movement through and around loads of citrus fruit in refrigerated trailers with conventional air circulation systems.

According to Goddard (2), in the USDA van container the volume of air delivered from the sidewall air plenums at their intersections with the crosswise channels in the floor is about 4,720 cm^3/sec (10 ft^3/min) per 929 cm^2 (1 ft^2) of floor surface. Also according to Goddard (2), the design of the USDA experimental van container enables it to deliver the cooled air supply to the bottom face of the load at a rate of 18,900 cm^3/sec per 0.3 linear m (40 ft^3/min per linear ft) of the floor surface. The goal in designing this container, according to Goddard (2), was to produce a totally integrated system that would have the capability of reducing the pulp temp of a full load of fresh fruits and vegetables 11°C (20°F) in 48 hr.

Performance of Conventional and Experimental Refrigeration Systems

Stationary cooling tests with the USDA experimental refrigerated van container have given very good results. Such tests with both simulated and real loads of both oranges and grapefruit have shown excellent rates of air movement through the loads and through the packed containers. Goddard (3) found that air movement through corrugated fiberboard boxes packed with plastic balls of 76.2 mm in diameter that he used to simulate size 200 oranges generally ranged from 1,416 to 2,360 cm^3/sec (3 to 5 ft^3/min) in the USDA container. Measurements made in packed boxes in a container equipped with a system that discharged cool air under the load at the front of the container ranged from 254.9 to 349.3 cm^3/sec (0.54 to 0.74 ft^3/min). Measurements made in boxes (cartons) packed with oranges in the experimental container showed air movement through the boxes to be about 2,360 cm^3/sec (5 ft^3/min). Grapefruit packed less densely than oranges and, therefore, presented less resistance to the movement of the air through the boxes. Measurements of the volume of air moving through individual boxes ranged from 3,776 to 6,136 cm^3/sec (8 to 13 ft^3/min) at different load locations.

Further stationary tests with half-precooled celery in which comparisons were made between results with the USDA experimental van and with 2 conventional van containers (one with an open-stacked load and one with a tightly stacked load) and between results with the USDA van and results with a third van container, equipped with a lengthwise, under-the-load air-distribution system were conducted. The results of the tests are summarized in Fig. 1.

The comparisons showed that the celery in the tightly stacked load in the USDA container cooled more rapidly and that the spread between high and low pulp temp was narrower than for the comparable lots of celery in the other 3 containers.

In 5 shipping tests in which oranges and grapefruit from the lower Rio Grande Valley of Texas were shipped to California and midwestern U.S. destinations in the USDA experimental van container, the average cooling rate was 0.46°C (0.8°F) per hour (1). The average cooling time for all 5 loads, which had an average weight of 16,782.92 kg (37,000 lb), was 36 hr. The spread in product pulp temp from the front to the rear of the load was only 0.9°C (1.6°F), indicating good uniformity in cooling rates throughout the length of the load. For all 5 shipments the average spread between the high and low pulp temp was only 1.46°C (2.6°F).

Shipping tests with celery packed in corrugated fiberboard boxes, which are quite densely packed and difficult to cool, also gave good results. The average spread between the high and low temp throughout the load was only 0.56°C (1°F) (3).

A paired shipping test was made with four kinds of mixed vegetables from Oakland, California, to Pusan, Korea (9). In the test, a comparison was made between results with the USDA experimental container and results with a commercial refrigerated container that had an over-the-load air supply system. The discharge air in the commercial container entered the cargo area through holes in an air plenum that extended the full length and width of the container ceiling. The experimental container cooled its load somewhat faster than the commercial container and provided greater uniformity in product temp throughout the load than the commercial container. More important, however, cooling in the USDA experimental container was accomplished with a tight stowage pattern, whereas a spaced, or open stowage, pattern was necessary in the commercial container. Although the same number of shipping containers of each kind of vegetable was shipped in each van container, the experimental container could carry more shipping containers because of its ability to cool a tightly stacked load.

The results with fresh vegetable shipments have been cited here because these products generally present more difficult problems in cooling than most citrus fruits. Vegetables not only have much higher heat of respiration than citrus, but also are usually packed more densely in the shipping containers. Penetration of the packed containers by the cooled air is, therefore, usually more difficult with vegetables than with citrus.

Advantages of Improved Refrigeration and Load Mass Interfacing Systems

Although both the front-end, or longitudinal, air delivery system and the lateral, or crosswise, air delivery system have their own characteristics and limitations, both offer several advantages over the conventional, over-the-load interfacing system. These advantages are:

1. They distribute the cooled air supply more uniformly over a greater area of one face of the load mass.

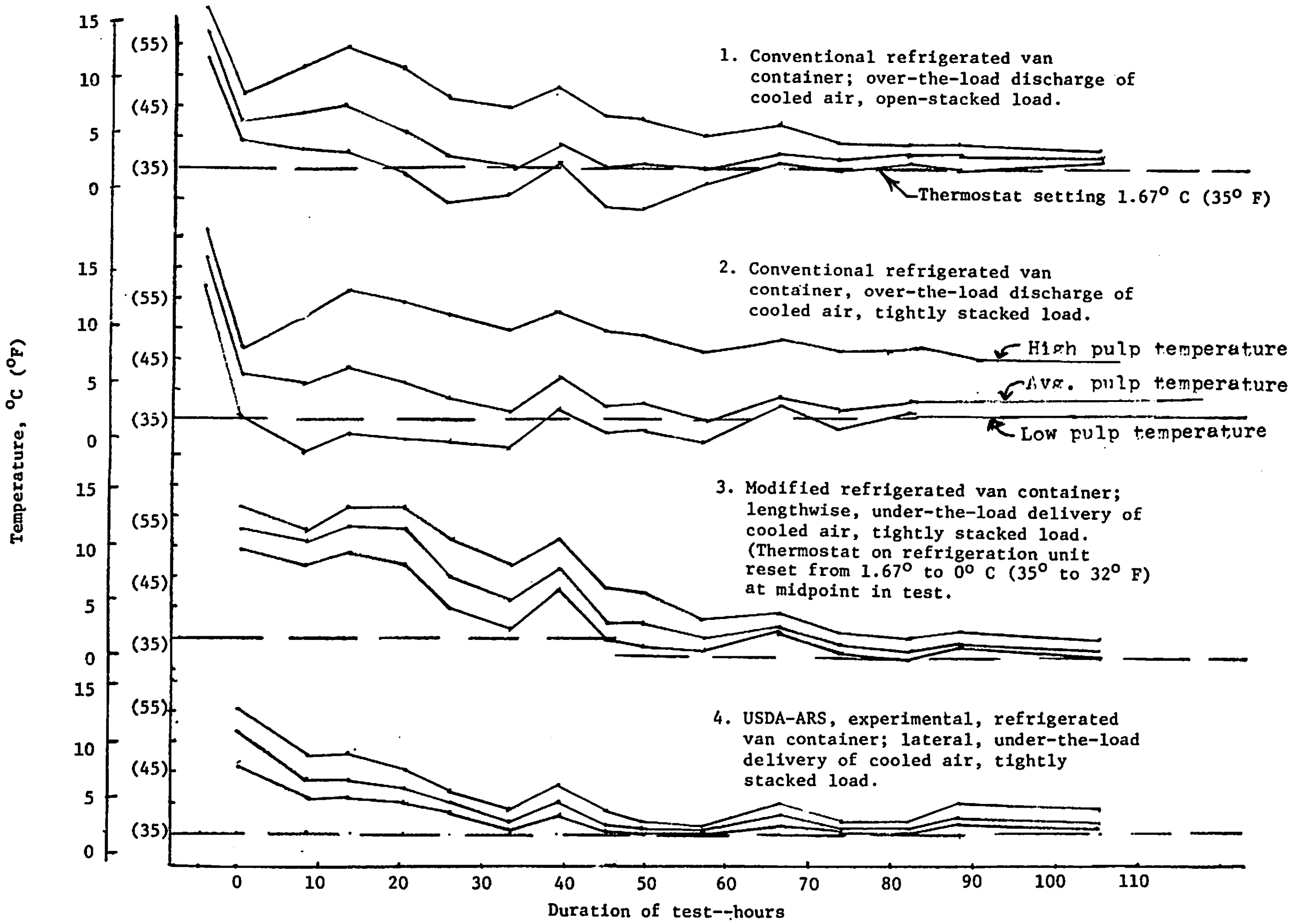

Fig. 1.—Temperatures of pulp in loads of half-precooled celery in stationary cooling tests in refrigerated van containers, by type of interface of cooled air supply with load mass.

2. The cooled floor area and adjacent vehicle structural members serve as a heat sink, and, thereby, provide a refrigeration reserve when the refrigeration unit is not in operation.

3. They help prevent product freezing during severe cold weather by providing air circulation at the critical point where the cargo might otherwise freeze at low ambient temp.

4. They provide for pressurized air delivery for more rapid and uniform cooling and fumigation of the load mass through upward, through-the-load movement of the cooled air supply.

5. They provide for more effective use of the cooling capacity of transport refrigeration units.

6. Shipping containers can be stacked in register and, thus, provide for maximum use of the resistance of corrugated fiberboard boxes to bear overhead weight from the high stacking of containers without distortion or damage.

7. Circulating air can penetrate the packed containers and, thereby, increase the rate of product cooling and help reduce the rate of moisture migration from the air to the shipping containers.

8. They facilitate the transport of heavier, more dense loads, and thereby:

  a. They help achieve economies of scale, resulting in reduced transport and refrigeration cost per measurable unit of product.
  b. They provide for more efficient use of energy for both transportation and refrigeration.
  c. They offer the potential for reduction of shipping container and product damage by helping reduce container movement and load shifting during transit.
  d. They provide for more dense and compact stacking patterns, which increase handling-unit stability in unitized and palletized loads.
  e. They provide for more dense, compact, and stable hand-stacked loading patterns, which help reduce loading time, load shifting, and the resulting shipping container and product damage.

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