VI Respiration-Humidity-Degreening-Refrigeration

Four closely related topics are brought together in this chapter. Respiration rates are a measure of catabolic life processes in living tissues. Humidity touches every facet of postharvest handling. Degreening, the single most important packinghouse operation, and refrigeration, the second line of defense against spoilage (the first is careful handling) and the first against deterioration in quality, involve a knowledge of life processes of citrus fruit, including the effects of temperature and humidity, and engineering principles and their practical application in the handling of large quantities of produce. Degreening and refrigeration have a great deal in common, despite one being centered around the acceleration of a natural process and the other a slowing down of the life processes of fruit and pathogenic organisms, as will become clear in the course of this discussion.

A. Respiration

Living organisms take in oxygen and give off carbon dioxide and other waste products and heat in the process of respiration. Comments were made earlier concerning the difference between climacteric fruits, such as apple, pear, mango, avocado or banana, which undergo a characteristic increase in respiration rate during ripening and non-climacteric fruit like citrus that do not show either an increase in respiration rate or a well-defined ripening period (Fig. 1). The rate of respiration like other chemical processes is responsive to temperature, being roughly doubled for every 10°C rise (or halved for an equivalent decline). Citrus fruit have a rather low rate at any given temperature as compared to bananas, mangos or avocados (Table 13). These non-climacteric fruit die of pathological causes, whereas climacteric types burn up their sugars and other sources of energy and die of old age.

One means of prolonging shelf life in both types is simply to reduce the temperature at which they are stored. This is vitally important in the case of non-climacteric fruits in 2 respects, the conservation of sugars in the fruit themselves and reduction of life processes of normal respiration with consequent rapid decay and death of the fruit. CA storage of citrus fruit has been largely unsuccessful. The sensitivity of citrus fruit to excessive levels of carbon dioxide (above 1-2%) requires that conventional storage and shipping containers be well ventilated. (The few studies of atmospheres around fruit in polyethylene bags and other containers which have been made indicate carbon dioxide level per se may not be the real culprit but rather the associated volatiles.)

Ethylene is one of the numerous volatiles emanating from citrus fruit and indeed is produced internally in most if not all plant tissues. Endogenous ethylene acts as a "trigger" to initiate ripening, the threshold concentration being very low, from less than 0.001 to 0.1 ppm. It initiates the natural break in color whereby chlorophylls are destroyed or transformed and carotenoids already present are increased. How chloroplasts become chromoplasts in peel cells of citrus is unknown but ethylene is involved. Normal respiration rate and evolution of ethylene are low unless citrus fruit are subjected to some sort of stress, as for example being bruised. Both ethylene evolution and respiration rate then jump to much higher levels, producing what may be termed a "false climacteric". Endogenous ethylene also influences softening of intercellular membranes, notably in the abscission zone which forms below the calyx (button) and results in the latter either remaining on the stem when the fruit is picked or loosening and falling off later.

B Humidity

Humidity affects all aspects of horticulture, yet it is all too often ignored, misunderstood or misapplied. Humidity is more a fact of life than a controllable variable in preharvest horticulture, but its influence should always be considered. Humidity is often a controllable variable which has assumed increasing importance during recent years in postharvest horticulture. The solution of problems involving humidity is, nevertheless, often hampered either by inadequate comprehension of the essentials of humidity or, more often, by a lack of coordination in applying the disciplines of horticulture, physics, engineering, plant pathogenic organisms around the fruit. The likelihood of invasion by decay organisms increases almost geometrically (or even exponentially) with higher temperature, thus the continual admonition to cool citrus fruit to a safe temperature as soon after harvest as possible. By contrast, long-term storage studies have shown only minor changes in sugar content of oranges even after 12 weeks at 32°F (0°C). There is a hazard, however, in reducing the temperature of tropical fruit, such as grapefruit, mango, avocado or banana, to a level which would give them protection from decay organisms, specifically their sensitivity to chilling injury. Fruit in this category, which also includes limes and lemons and many other non-citrus species, exhibit symptoms of metabolic stress, such as pitting or an overall breakdown of peel tissues as well as various types of internal browning, etc., when they are subjected to temperatures well above freezing. The degree of sensitivity varies not only among species, bananas chilling after only a few hours' exposure to temperatures below the mid-50'sF (12-13°C) and others requiring a few to several weeks, but also during the season for the same species, the behavior of grapefruit being an excellent example.

Climacteric-type fruit can also be "put to sleep", have their rate of respiration greatly reduced, through a combination of lowering the concentration of oxygen and increasing that of carbon dioxide. Apples and pears can be held for extended periods in controlled-atmosphere (CA) storage where low levels of oxygen and high levels of carbon dioxide are maintained along with temperatures near freezing. CA storage has proved less successful thus far for climacteric-type tropical fruit, primarily because of their sensitivity to chilling injury and the general requirement of harvesting the fruit at the proper stage. The latter has proved particularly troublesome for fruit like avocado, mango or banana whose bloom periods extend from a few to several weeks.

Numerous attempts have been made to utilize CA storage for non-climacteric-type fruit. Respiration rates can be reduced as in conventional storage but lowering either the oxygen level or particularly raising that of carbon dioxide results in fermentation, instead of physiology, plant pathology and sometimes others such as meteorology or economics. These sentences, quoted with slight emendation from Grierson and Wardowski (1975), underline the ubiquity and vital importance of humidity and its ramifications to horticulture in general. The following paragraphs are largely based on this source.

1. Expressions:

Humidity can be expressed in several different ways, such as percentage relative humidity (% rh), specific humidity, dew point, vapor pressure and various combinations of these. Each is useful, provided one understands their limitations. The observation on which all are based is most commonly the difference between dry-bulb (DB) and wet-bulb (WB) thermometer readings. Depression of the WB reading results from evaporative cooling and is directly related to both temperature and water vapor pressure in the air. Instructions for use of a sling psychrometer to obtain DB-WB readings specify an air velocity of at least 500 ft/min (ca 150m/min), preferably 1000 ft/min (300m/min), the WB wick wetted with distilled water and free of dirt and accumulated salts, and thermometers calibrated to fifths or tenths of a degree if an error less than ±7% in rh is desired. The common DB-WB thermometer pair with water reservoir for the WB wick is woefully inaccurate in still or slowly moving air.

<u>Percentage relative humidity</u> (rh) is the ratio, expressed as %, between the quantity of water vapor present and the maximum possible at that temperature and barometric pressure (with correction for partial pressure of water vapor present). Water vapor and air coexist independently <u>Relative humidities can only be compared at the same temperature and barometric pressure.</u> (Tables for rh always specify the barometric pressure for which they are designed and usually give the equation for correction to a different pressure.)

<u>Absolute</u> or <u>specific humidity</u> is the measure of the weight of water in a given weight of air, usually being expressed as grains (gr) per pound of dry air (=0.1428 g/kg). Typical psychrometric charts are shown

in Figs. 20 and 21, in which absolute humidity is shown as a vertical axis at the right. Relative humidity appears as a series of curved lines which separate as the DB temperature (horizontal axis) increases. Each of the 5 conditions specified in Fig. 21 differ in DB temperature but have the same rh. Condition A, for example, shows absolute humidity as 30 gr/lb (4.28 g/kg) at 33°F (0.6°C) and 95% rh, while E at 85°F (29.4°C) shows 180 gr/lb (25.70 g/kg), meaning that 6 times as much moisture must be vaporized at 85°F to give 95% rh as at 33°.

Dewpoint (DP) is commonly used as a measure of humidity, particularly by meteorologists. DP is the temperature to which moist air must be lowered (at constant pressure) to initiate condensation (100% rh). DP is found by moving horizontally to the left from a specified temperature and rh condition until the 100% rh curve is intercepted. The DP, for example, of 85°F and 60% rh would be slightly above 70°F (21.1°C). (Note that absolute humidity at this DP is 110 gr/lb = 1.571 g/kg, meaning that some 70 gr/lb = 10 g/kg moisture would have to be added if rh were to be raised to 95% while maintaining 85°F!)

Vapor pressure is the partial pressure of the water component of any dry air plus water vapor combination. There is a direct correlation between absolute (specific) humidity and vapor pressure regardless of temperature at any given barometric pressure (Fig. 20). Vapor pressure is often used as an expression for humidity gradients which are denoted as "vapor pressure deficit" (vpd), that is, the difference between vapor pressures at 2 points. Vpd determines the rate of evaporation, hence of transpiration but does have the problem of being a comparative measure which does not indicate the amount of water vapor involved. (Vpd is frequently expressed as mm Hg in addition to the units shown in Fig. 20.)

2. Some Physical Properties

The specific gravity of moist air is lower than that of dry air. Water vapor is a gas subject to Avogadro's Law which states that equal volumes of different gases at the same pressure and temperature contain the same number of molecules. Each molecule of water vapor will displace a molecule of one of the components of dry air (essentially, oxygen and nitrogen) in a given volume of humidified air. Atomic weights of water, oxygen (O_2) and nitrogen (N_2) are 18, 32 and 28, respectively, hence the more water vapor a given volume of air contains, the lower is the specific gravity.

The amount of water vapor which can exist in a given space is directly dependent upon temperature and exerts its own vapor pressure independently of the presence of air. The latter is derived from Dalton's Law which states 2 or more gases occupying the same space at the same time behave independently of each other.

Total heat content (enthalpy) of dry air is based on its specific heat (approximately 0.24 between 0° and 100°F = -19° to 37.7°C). The specific heat of water vapor is about double that of air (0.48) meaning it takes more transfer of heat (sensible and latent) to change the temperature of moist than of dry air, whether heating or cooling is involved Alterations of the water vapor content are, however, of minor consequence in heat transfers, provided there is no change of state. Latent heat is released when moist air is cooled below the dew point or when water is vaporized, the latent heat of condensation or of vaporization being about 590 cal/g. Latent heat is also released in the change of state from liquid to ice or *vice versa*, being about 80 cal/g as heat of fusion. Several situations involving the latent heat content and humidity of the air occur in citrus groves and packinghouses. One is that shown in Fig. 22, where the air temperature is at 35°F (1.7°C) and 90, 50 and 10% rh, respectively. Here, the release of latent heat at point A' results in a "white frost" with no damage but the dew points are too low at either B' or C' to prevent serious damage. Another situation in a packinghouse would be the frosting up of refrigerator coils, which would involve both heat of condensation (vapor to liquid) and heat of fusion (liquid to solid).

3. Interactions with Temperature and Air Movement:

Changes in temperature produce associated changes in humidity. A case where considerable dehydration occurs as a result of a severe diffusion gradient in terms of absolute humidity (110 gr/lb = 15.71 g/kg in bags vs. 30 gr/lb = 4.28 g/kg in a refrigerated vehicle) is shown in Fig. 23. Curves in Fig. 24 illustrate the gyrations in % rh with alternating 70°F (21°C) and 40°F (4.4°C) storage of grapefruit in loose polyethylene bags (no bagmaster carton). Another interesting example (Fig. 25) which also results in increased moisture loss occurs because of minor fluctuations in temperature. These cause much wider fluctuations in % rh with a consequent drop in absolute humidity when rh is low and thus an increased gradient out of the fruit.

Air movement affects humidity in a closed system such as a cold storage. The higher the volume circulated per minute, the higher is the humidity. There is a smaller temperature differential then between return and delivery and consequently less precipitation of moisture on the coils takes place under those conditions. The net result is to raise humidity, thereby decreasing transpiration and reducing shrinkage. The opposite effect is produced, however, if air velocity at a constant humidity is raised.

4. Desiccation, Wound Healing, and Chilling Injury:

Manifestations of desiccation in citrus are commonly seen in 2 different forms. One is the freezing of internal tissues with more or less complete disruption of membranes and subsequent drying out while fruit are on the tree. The rind in this instance remains intact and apparently free from damage. The other, which presents a serious economic problem, is stem-end rind breakdown of oranges. This disorder results when susceptible fruit are subjected to drying conditions between the tree and the washing and waxing operation. Such fruit appear normal but a ring of tissue around the stem-end collapses several days later (Fig. 26). Decay often sets in immediately (Table 14).

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<u>Healing of minor wounds</u> was noted when citrus fruit were degreened at very high humidities used to minimize stem-end rind breakdown. Healing involves synthesis of lignin, which occurs only at humidities well above 90%.

Extremely high humidities (96 to 98% rh) have likewise been found to restrict greatly the development of <u>chilling injury</u> of citrus fruit. Equipment and monitoring devices are now available to maintain humidities in the desired range to suppress stem-end breakdown prior to washing and waxing. Maintenance of continuous very high humidities inside packages during transit requires, however, that some means must be devised for damping fluctuations illustrated in Figs.23, 24 and 25 before high humidity shipment of chilling injury-sensitive fruit becomes feasible.

C. <u>Degreening</u>

Degreening is the single most important operation in citrus packinghouse handling, as it is done during the period when a large proportion of the season's profits are made. Degreening is done mainly in the early fall when certain varieties are edible and legally mature but still have more or less complete green color. The procedure is variously denoted "degreening" (the preferred term), "gassing", "coloring" (an unfortunate designation from invariable confusion with "color-add", a quite different operation), "sweating", "curing" or "quailing".

Packinghouse operators were aware early in the 20th century they could place stacks of filled boxes under a tarpaulin for a few days and color up fruit too green to meet the existing maturity standard of "half color". It was discovered about 1915 fruit shipped across the country from California in rail cars equipped with kerosene heaters were well colored upon arrival, even though they were originally quite green. It was thought at first heat was responsible, then it was realized degreening occurred only if the heaters were improperly adjusted and producing fumes. Denny reported in 1923 after thorough investigation and numerous experiments the active ingredient in the kerosene fumes was ethylene.

At least 1,000 to 2,000 ppm was recommended for degreening citrus fruit, although one of Denny's own experiments with lemons showed the process could be initiated with as little as 0.1 ppm. Degreening with ethylene, in which the natural process of fruit coloring on the tree can be greatly accelerated, became standard packinghouse procedure following Denny's discovery.

Degreening has been a major research concern at AREC Lake Alfred (formerly Citrus Experiment Station) and other centers for many years. Hundreds of compounds have been screened as degreening agents but ethylene is still by far the best one from the standpoint of efficiency and also the least expensive material available for the purpose. Recommendations for operating conditions and other facets have been continually modified on the basis of the latest findings from the degreening research program. The latter has accelerated substantially in the last decade in response to the general shift of packinghouses to pallet boxes, the design of new types of degreening rooms for these boxes and increased problems of various disorders connected with harvesting and handling.

1. Operating Conditions:

The basic operating conditions for degreening rooms were developed during the 1950's and earlier when fruit for fresh shipment was handled almost exclusively in field boxes, rooms were built to hold 500 to 1500 boxes, controls were manual and ethylene was dispensed by either the "shot" (periodic additions of gas) or "trickle bottle" (continuous addition of gas monitored by counting bubbles). Recommendations in 1960 (Grierson and Newhall, 1960) were 20 to 200 ppm ethylene, 83-85°F (28.5-29.4°C), 85-90% relative humidity, continuous air circulation and ventilation, and maximum degreening periods of 60 to 72 hours for oranges and 48 to 60 hours for grapefruit. These were based upon extensive experimentation and reflected the best judgement of all concerned. The 85°F temperature was found to be optimum under Florida conditions, with a drastic reduction in rate of degreening either above or below this point. The curve for oranges is V-shaped with the apex centered on 85°, while that for grapefruit is U-shaped. (The optimum for California is 75°F (24°C).) Air circulation to give about one change a minute and ventilation adequate to keep the level of carbon dioxide below 1.0% (about one complete change of air per hour) were also found necessary.

Grierson and his co-workers have maintained throughout their research on degreening that ethylene must be supplied at the lowest possible level and the degreening period must be the shortest possible. The primary reasons are that diplodia stem-end rot (*Diplodia natalensis*) has an optimum temperature of 86°F (30°C) and ethylene specifically stimulates its growth. Development of laboratory techniques for measuring minute quantities of ethylene in the early 1960's lead to the discovery that the threshold concentration for initiation of degreening was 0.1 ppm or lower. This and the perfection of inexpensive, fast, reliable instruments for measuring ethylene for dispensing small quantities of gas accurately led to a drastic reduction in the recommended concentration to the present 1 to 5 ppm. Automatic monitoring devices can maintain 1 to 2 ppm in large rooms.

Recommendations for relative humidity levels in degreening rooms have also changed. Evidence was laboriously accumulated in the course of many hundreds of experiments that the incidence of a number of physiological disorders, notably stem-end rind breakdown of oranges, was drastically increased under conditions of low humidity. Lots in which delays of a day or 2 occurred between harvest and washing and waxing and fruit from groves receiving large quantities of nitrogen relative to potash, and particularly combinations of these conditions, frequently had inordinately high rates of stem-end rind breakdown and subsequent rapid decay, neither of which were evident until the fruit were well on their way to or in the retail store. By contrast, similar lots which were either handled promptly or immediately put under high humidity conditions had much lower rates. A separate series of experiments to determine the feasibility of using oranges harvested mechanically

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revealed that not only was stem-end rind breakdown reduced but minute nicks, cuts, abrasions, etc., incidental to fruit being swept up from the ground also healed when fruit were held at humidities just under the condensation point. (Inspection shows current commercial hand harvesting produces about as many minor wounds.) Recommendations for relative humidity were then raised to 90 to 96% and equipment in the newer degreening rooms can maintain 96 to 98%, which is in the range where lignin development occurs in the wound healing process. Grierson emphasizes citrus fruit must be brought into high humidity surroundings promptly after harvest, particularly those lots predisposed through grove cultural practices or other conditions to rind breakdown susceptibility. (Fruit which are colored sufficiently not to require degreening can be stored in the same rooms.)

Certain varieties, notably 'Temple', tangerines and tangerine hybrids, are unusually sensitive to degreening conditions, particularly when humidity is too low or temperature too high. Degreening of satsumas is not recommended and all of the other specialty fruit should be degreened as short a period as possible, in no case longer than 36 to 48 hours.

2. Factors Affecting Degreening:

It is well known the degreening period must be longer early in the season than later on and such fruit are lighter in color when they come out of the room. The efficiency of degreening can be improved greatly if fruit are presorted for color and size. The darker green are the fruit, the longer is the exposure to degreening required. Smaller fruit require a longer exposure than larger ones of a given shade of green. Fruit from young or vigorously growing trees or trees given a late oil-emulsion spray (particularly early oranges and tangerines sprayed after early to mid-July) or those which have regreened ('Valencia' and other late-season oranges) are virtually impossible to degreen. Washing retards degreening for reasons not understood although it is often done anyway. Polishing or waxing essentially inhibits degreening

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3. Degreening Rooms

Many different types of rooms have been built especially for degreening or in some cases modified for the purpose since the early 1920's. The earlier rooms were constructed of wood, concrete or metal with slatted wood or solid concrete floors (Fig. 27). Shape of the rooms varied from square to rectangular, the latter often being woefully inefficient because of dead spots in the corners. Capacity ranged from about 500 to a maximum of 1500 field boxes. Older types of rooms included the Hale, Webster and FMC. Some versions consisted of canvas walls and ceiling and were more efficient than those built of other materials as they provided better ventilation.

Changes in degreening room design began in the late 1950's when the false ceiling room (Fig. 28) was devised by the Citrus Experiment Station at Lake Alfred (now AREC Lake Alfred) to overcome some of the drawbacks of other solid floor types. This room had the fan, heater and other equipment mounted over a false ceiling which had openings around the edges and a movable center stack so the space could be used for other purposes between degreening seasons. The most radical departure from traditional degreening room construction also appeared in the late 1950's in the form of bulk degreening bins (Fig. 29). These were modeled after regular cannery bins but were equipped with a series of cider press cloth-covered baffles arranged in zigzag fashion. Fruit were loaded by conveyor through a trapdoor at the top and unloaded at the bottom. Capacity was approximately one-third of the bin volume, or about 100 to 150 boxes. They worked well only for oranges.

Older types of degreening rooms were modified in existing packinghouses to accommodate pallet boxes as these came into use in the early 1960's. Low ceiling heights which were adequate for 4- or 5-high stacks of field boxes were too low, floors in many cases were not strong enough to support fork lift trucks loaded with 1 or 2 1000-lb (454 kg) pallet boxes of fruit, and fans were generally too small to provide proper air circulation for the increased volume of fruit being degreened. Some of the new packinghouses constructed enlarged versious of the false-ceiling type to accommodate 3000 to 5000 boxes. These rooms were not particularly efficient since they retained the central stack as a means of air entry to the pallet boxes, although they were designed for stacks 4 to 6 high as had been standard practice in deciduous fruit cold storage for years. Pallet boxes with 4-way runners would have provided proper air movement, whereas those with 2-way runners (standard in commercial use) had air movement blocked in the crosswise direction. (Concurrently, the U.S. Dept. of Agriculture conducted a series of experiments in cooperation with AREC Lake Alfred with pallet boxes of several designs, after which a square box, initially with slotted bottom and sides but later with slotted bottom only, was recommended for general use in Florida.)

The end-to-end air flow concept was the single biggest improvement in the history of degreening room design. The initial version incorporated in new degreening rooms constructed at Lake Wales CGA and a few other packinghouses was a batch-type operation, as was its predecessors (Fig. 30). It is similar in some respects to the false-ceiling room in that the fan, heater, etc., were mounted above a false ceiling but fixed for horizontal movement of air. Canvas curtains were lowered at each end of the false ceiling until the opening above the pallet boxes, which were stacked 2 to 4 boxes high in tight parallel rows, was blocked. Space was left at both ends of the rows of boxes, the one nearest the front acting as the delivery duct and the other as the return. Air circulates between the aligned pairs of pallet runners, each row and layer thus having its own lengthwise duct from which air flows up through the slots in the bottom of the boxes. These rooms were highly successful, with efficient degreening and no real limit on capacity, although they were usually made large enough to hold most of a day's run. Controls for temperature, humidity, ethylene, ventilation and air circulation were automatic. The only real drawback to this design was having the air delivery to the front, which meant degreening had to be suspended while the room was being loaded or unloaded. Nevertheless, this is still (1978) a widely used design, particularly for small or medium-size packinghouses.

The next version involved several modifications. The major one was to reverse the direction of air delivery to the back of the room where vertical ducts with T-shaped separators spaced pallet box width apart supplied air to the individuals rows of boxes. An aisle about 16 ft. (ca 5 m) wide for maneuvering fork lift trucks inside the room and air-curtain entry and exit doors were added at the front to permit loading and unloading while the room was in operation. This version was thus designed as a continuous-operation room (Fig. 31) operated as a single unit. It was noted, however, there was little lateral movement of air from one row of pallet boxes to another, provided the boxes were placed tight against the delivery duct and each other in a row. This meant that each row, or groups of rows, could be degreened independently if desired. A room with 3 units operated as a single unit is shown in Fig. 31c and the same operated as 3 units, in Fig. 31d, the only difference being the lengthwise partitions above the false ceiling. The lengths of time required for loading and unloading a 10,000 box equivalent-capacity room are long enough to warrant the extra expense of 3 sets of controls. The latter mean the different sections can be turned on (or off) when not needed, with a resulting substantial saving in operating costs.

A point Grierson has emphasized since the first pallet-box degreening rooms were constructed is their similarity to cold storages. All they need is additional refrigeration equipment, an adequate vapor barrier, and insulation in the walls to convert them to bona fide cold storages. Degreening is done mainly in the fall and for a total of no more than 6 or 8 weeks during the year. Temperatures of fruit entering the packinghouse may approach 100°F (37.8°C) on occasion; low humidity situations may also require so much steam to raise rh to the operating range in a degreening room as to increase the temperature well above 85°F; thus, refrigeration capacity to cope with these problems is definitely recommended

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Fixed expenses of these jumbo rooms are large enough to warrant utilizing them for something besides temporary storage of fruit or holding places for odd pieces of equipment, boxes, etc. They could provide the cold storage space which has historically been sorely lacking in most of Florida's packinghouses.

D Refrigeration

The primary functions of refrigeration for citrus are 1) to maintain the eating quality as harvest throughout the transit and marketing period and 2) to delay the onset of decay. Cold storage to prolong the season is very minor, with the exception of lemons (whose handling differs markedly from that of other citrus fruit and are discussed in a separate section in the chapter on Packinghouse Procedures). Refrigeration slows down the respiratory activities of both fruit and pathogenic organisms so that the life of the fruit is prolonged much beyond that possible under conditions where rots and molds grow unchecked. Non-climacteric fruit such as citrus do not contain substances like starch which can be converted to sugars and other readily consumable energy sources whose changes can be suspended for long periods of time as under controlled atmosphere (CA) storage. Citrus fruit must be cooled as quickly as possible to a safe temperature once the necessary washing, waxing and other preparation for market is completed and held under proper conditions of humidity and ventilation to minimize deterioration from undesirable physiological changes and invasion of decay organisms. The first line of defense in maintaining postharvest quality of citrus fruit is of course careful handling, the prevention of the cuts, bruises, abrasions, rind breakdowns, etc., through which fungi can readily enter. Refrigeration is the second line of defense along with protection by fungicides and both have assumed increasingly greater importance as commercial harvesting practices have become rougher in recent years.

The extent to which refrigeration is used is largely dependent upon local marketing methods. It is usual in Florida and Texas to take orders for shipment of fresh fruit while it is on the tree. Picking rews are nstructed to harvest enough fruit to cover the sales orders

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currently on hand (with due allowance for off-grade fruit, off-sizes, etc.). The fruit is then shipped as fast as possible, seldom pausing for precooling. A few packers precool regularly but most rely on mechanical reefer trucks (semi-trailers with built-in cooling units) for refrigeration. This can be efficient in cool weather but the trucks simply do not have the capacity to cool a load of warm fruit more than a few degrees a day during warm weather (which includes much of the fall, late winter and spring in Florida). The Florida industry has today less refrigeration capacity than any other major fruit industry in the world. It is an increasingly difficult situation in a world of expanding--and ever more quality conscious--markets.

It is customary, on the other hand, in California and Arizona to sell out of an inventory of refrigerated packed fruit. Citrus (mainly oranges) is palletized and set to cool as it is packed. The differences in handling practice reflect, to some extent, both the comparatively long hauls to market for California-Arizona fruit and the fact a great many western packinghouses pack one type of citrus (i.e., oranges or grapefruit or lemons) in only one type of container (7/10 bu. fiberboard cartons). Typical Florida houses may pack oranges, 'Temple', tangerines tangelos and grapefruit in a single day and offer them in a variety of containers. This makes "selling out of inventory" much more difficult.

Definitions and Terminology

Refrigeration is the general term for cooling fruit in transit or storage, the former referring to movement direct to the market and the latter to holding periods of a few days to several weeks or months before or after transportation from the packinghouse to market. Precooling is refrigeration prior to transit or storage in a facility designed for rapid reduction of fruit temperatures (with due regard for physiological effects).

Two types of heat are involved directly in cooling fruit, field heat and heat of respiration. A third type, latent heat, is also concerned where water vapor in the air undergoes a change of state, as in condensation of moisture on fruit or evaporator coils of the refrigeration unit. Field heat, which is often denoted (erroneously) simply as sensible heat, does not involve any life process but is merely the quantity of thermal energy removed in cooling (or added in heating) an object from one temperature to another. Heat of respiration comes from conversion of sugars, 673 g cal per g equivalent of glucose (plus 6 molecules of O_2) being produced in this process. Sensible heat thus consists of both field heat and heat of respiration. The unit of measure for all 3 types of heat is British Thermal Units (BTU), the energy required to cool (or heat) 1 pound of water 1°F (from 59 to 60°F) or the equivalent, 0.253 kg. calories, in metric units. Field heat involves 3 quantities, the difference in temperature, mass (weight) and heat capacity (specific heat). Some thermodynamic data for citrus are given in Table 15. Specific heats for other common materials used in containers are 0.3 for dry wood, 0.2 for fiberboard (cartons) and 0.15 for steel.

A ton of ice (2000 lb = 908 kg) absorbs 12,000 BTU (3036 kg cal.) per hour or 288,000 BTU (82,864 kg cal.) per day (24 hours x 12,000 or 3036) as it melts. The same values are used in rating mechanical refrigeration units (Fig. 32), although efficiency and hence the real capacity will vary, as shown in Figs. 33 and 34 from Packinghouse Newsletter #49, Nov. 30, 1972.

Two of the 3 types of heat transfer, conduction and convection, are involved in refrigeration of citrus fruit. Radiation from nearly spherical objects in the temperature range involved is so low it can be ignored. Conduction is the movement of heat from one molecule to another through a solid or liquid, the rate being basically dependent upon the thermal conductivity of the material. Conduction is involved in the transfer of heat from the center to the surface of a fruit (or vice versa) or through the metal fins of a refrigeration coil. Citrus and other fruit are about 90% water, which is a relatively poor conductor of heat, thus the rate of heat transfer with a given temperature gradient will be slow. Metals, on the other hand, are good conductors, hence the rate of heat transfer through the cooling fins is high. Convection is the movement of heat by the active motion of molecules in currents of air or some other medium (including solids or liquids). Heat transfer of this type may be natural, as induced by differences in density of the medium, or forced, where the natural movement is accelerated by a fan or pump. Convection is involved in heat transfer from the surface of a fruit to the medium and from the medium to the cooling fins of the refrigeration unit.

Rates of heat transfer in refrigeration of citrus fruit depend upon 3 factors, the temperature gradient from the center to the surface of a fruit, the velocity of the cooling medium, and the temperature gradient through the cooling coils of the refrigeration system. Conduction is involved in the first and last cases. Conductivity of an inhomogeneous fruit like citrus varies according to the relative proportions of the major components (peel and flesh) and presence or absence of a hollow central core. Rapid removal of heat requires the largest possible temperature gradient from the fruit center to surface during cooling. This gradient, however, must not exceed the upper limit imposed by conductivity of the fruit tissues, any such attempt being likely to result in freezing injury or other physiological disorders. Convective heat transfer is limited by the heat capacity of the medium, over 4 times the weight of air being required to transfer a given quantity of heat as compared to water at the same velocity. Surface characteristics of the fruit, presence or absence of a fruit surface to medium temperature gradient (normally present in air cooling but absent in water cooling) and turbulence in the flow of medium (too low a velocity results in an unduly large surface to medium gradient and too high a velocity creates so much turbulence the heat carrying capacity of the medium is reduced) also affect convective heat transfer in a given system. Conductive heat transfer through the cooling coils and hence from the fruit is basically determined by refrigeration capacity relative to the load imposed on it.

Fruit heat is, of course, only one of several components in the total heat load. Others of significant importance include heat to be removed from containers, pallets, etc., losses through the walls, ceiling and floor of the room, truck or rail car, and work done by the fan or pump in moving the cooling medium around in the system. Proper design of a refrigeration system entails minimizing the non-fruit and container heat load and adjustment of operating variables to provide best efficiency with available cooling capacity.

2. Where Should the Temperature of a Fruit be Measured?

This is apparently a simple question but many packinghouse and other operators do not know the correct answer. Citrus fruit are nearly spherical, hence a suitable theoretical model would be a homogeneous sphere. The center of mass of such an object lies along the radius of a shell dividing its mass (or volume) in half, the mass-average point thus being at $r = \sqrt[3]{V/(2/3)\pi}$, or 0.7923r from the center. The average temperature of a sphere being cooled slowly is at this point as is that of a sphere being cooled rapidly and allowed to come to equilibrium under adiabatic conditions (not heat lost or gained from the surroundings)

Citrus fruit are, however, neither truly spherical nor homogeneous, hence their mass-average point will not be found at exactly 0.7923r. Experimental values for oranges, grapefruit and tangelos were determined during the course of forced-air precooling experiments carried out at Gainesville in the early 1960's. Temperatures were sensed with multi-point thermocouple probes inserted in both the polar (from stylar end) and equatorial axes of several fruit in a load. Average values (polar and equatorial combined) are 0.784r, 0.772r and 0.795r for oranges, grapefruit and tangelos, respectively, or somewhat less (nearer the center) than the theoretical point except for tangelos (Soule, Yost and Bennett, 1969). The latter, however, have a hollow center, thus the theoretical mass-average point is closer to the surface, about 0.8023r for fruit of medium size.

The mass-average temperature of a fruit undergoing cooling can be calculated from equation 1.

$$t_{ma} = t_c - (t_c - t_s)ma \quad 1.$$

where t_c is the center-of-fruit temperature,
t_s is the surface-of-fruit temperature, and
ma is the mass-average point for the particular kind of fruit

(Values for tangerines and 'Temple' were not determined but they should be about the same as for tangelos or slightly less, e.g., about 0.790r.) In practice, a thermometer or other temperature-sensing device inserted just below the peel would provide a true measure of the fruit's temperature whether during cooling or afterwards.

3. In-Transit Refrigeration:

Recommended conditions for in-transit refrigeration and storage of citrus fruit are given in Table 16. It is imperative, particularly in hot weather such as that prevailing early in the season before many fruit reach prime edibility or late in the season, to reduce fruit temperature to a safe level (below 50°F=10°C for oranges or tangerine types) as soon as possible after harvest. It is equally important, particularly with oranges, to raise the humidity to the highest practicable level. Fruit is shipped mainly in semi-trailers or piggy back semi-trailers (trailers on rail flat cars), with some in mechanical refrigerator cars. Transit time is 2 to 7 days for shipments to most parts of the U.S. and Canada. Refrigeration capacity of a semi-trailer is simply inadequate to remove the vast quantity of heat in hot fruit during the usual transit period. Calculations of the heat load for a typical trailer load of oranges are given in Table 18, the upper section (A) being without precooling and the lower one (B) with precooling. These show the truck would be at or near its destination before the load was cooled down unless some of the heat were removed via precooling prior to shipment.

4. Precooling:

Prompt refrigeration of oranges to 40°F (4.4°C) was recommended by Ramsey back in 1915. Large facilities where fruit could be cooled prior to shipment were constructed as an integral part of packinghouses in California and Arizona, as mentioned earlier. Precooling is still not usual in either Florida or Texas. A few packinghouses in Florida began precooling in the late 1950's and early 1960's when the shift to cartons and polyethylene bags (shipped in bagmaster cartons) got underway. (Fiberboard is an excellent insulator, especially when the container is tightly closed or has few ventilation holes, as packinghouse operators soon discovered when the first attempts were made to precool fruit in them

Cartons with side ventilation holes can be cooled very effectively when stacked properly, but the hand labor involved is becoming so expensive many packinghouses have turned to mechanical palletizing. Here, top and bottom ventilation holes are far more effective with most stacking arrangements and air-distribution patterns, since this configuration utilizes convection movement to get warm air out of the containers and cool air in.

Two main types of precooling facilities are, or have been, in general use, those utilizing air as the cooling medium and hydrocoolers. (The latter is not recommended for citrus fruit due to the tendency of "weak" crops to suffer increased decay if later the fruit is allowed to return to air temperature in the store or home.) The oldest, and most common, system is a cold storage where air at 32° to 34°F (0-1°C) is circulated around packed containers. Cooling is slow, 12 to 24 hours being required to reduce the temperature to about 40°F (4.4°C) in the older versions where air was blown horizontally at low velocity. Many of these old rooms have been remodeled and those in the newer packinghouses in the western states designed for vertical air movement under pressure from ceiling mounted jets. Pallets are stacked with precise spacing and the jets are located at the corner of each pallet. Cooling is considerably faster here than in the old horizontal-flow-rooms. Somewhat similar precooling rooms have been constructed in some Florida packinghouses, xcept these are designed for movement of air up through the loor. Very e ective fast precooling has been achieved with cartons on pallets but the advent of slipsheets (fiberboard sheets) pose a problem which can be rectified only if the slipsheets can be slotted to match the ventilation holes of the cartons.

Other means of precooling are in-trailer cooling being done in Texas and in-car cooling. Experiments with a batch-type forced-air precooler (Fig. 35) showed that citrus fruit can be cooled very rapidly without injury (in fact, the same lots were cooled rapidly several times in succession without injury) (Soule, Yost and Bennett, 1969). A prototype 5-stage forced-air precooler was used in cooling oranges and grapefruit on a moving conveyer (Fig. 36). Medium-sized oranges could be cooled as fast as 2°F (1.8°C) per minute without injury (Grierson, Bennett and Bowman, 1970).

Typical cooling curves for room cooling (horizontal flow), forced air (batch type) and hydrocooling are shown in Fig. 37. These illustrate how cooling can be greatly accelerated by imposing a small pressure differential (ca 1 inch=2.5 cm of water) in air movement. Hydrocooling looks good from the standpoint of heat removal but produces both physiological problems (e.g., chilling injury) and greatly increased susceptibility to decay.

5. Storage

The purposes of storage are to extend the market season and to avoid market gluts. Fruit can be held on the tree and retain good quality for several months after peak edibility in California if packinghouse operators choose not to store fruit in their cold storages. Tree storage is limited, however, in Florida by the tendency of fruit, except grapefruit, to drop or dry out rather quickly within a few weeks or months after they attain peak quality. The U.S. Dept. of Agriculture Horticultural Research Station at Orlando carried out about 20 years of research on storage of Florida citrus. Their principal findings were to store only sound fruit of high quality, do not store overmature fruit or late in the season, fungicides treatments are beneficial only with oranges (not true today, both thiabendazole and benlate being definitely