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Postharvest Curing at High Temperatures Reduces Decay of Individually Sealed Lemons, Pomelos, and Other Citrus Fruit

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Abstract. **Curing of sealed lemons of normal and decay-prone types [*Citrus limon* (L.) Burm.f] and of sealed Goliath pomelo [*Citrus grandis* (L.) Osbeck] inhibited postharvest decay without deleterious effects on fruit quality and prevented the development of *Penicillium digitatum* on inoculated fruit. Curing of nonsealed fruit was less effective in reducing decay than curing sealed fruit and caused prohibitive weight loss, shrinkage, and softening. Curing of sealed and waxed 'Shamouti' and 'Valencia' oranges (*C. sinensis*), in comparison to only sealed fruit, resulted in some CO_2 injury of the peel and off-flavor.**

Curing of potato, sweet potato tubers, and several flower bulbs has been in commercial use for several decades (5, 10, 16). Curing involves holding the produce at relatively high temperatures (15° to 40°C) and high humidities (21). Fawcett (14) discussed and reviewed much work on response of citrus pathogens to temperature.

As early as 1948, control of green mold of oranges caused by *Penicillium digitatum* was shown to be reduced by holding fruit for several days after harvest at 30°C and 90–100% RH (10, 17). These conditions subsequently were shown by Brown et al. (11, 12) to elicit the biosynthesis of lignin and its phenolic precursor in the outer pericarp (flavedo) of the fruit while reducing the growth of *P. digitatum* (11).

Maintenance of a high humidity level was essential to the development of the defense mechanism. Below 75% RH, the cells surrounding the injury were damaged by desiccation and did not synthesize lignin; however, despite this exciting findings, curing was not practiced commercially with citrus fruit except when degreening early season fruit with ethylene at 30°C.

Lidster and Porritt (20) showed that apples held at 38°C and 95–100% RH for several days immediately after harvest developed less decay during subsequent long-term refrigerated storage than fruit that was heat-treated at 5–10% RH. Seal-packaging of individual grapefruit (15) and tomatoes (7) reduced damage due to mechanical harvest, probably because of the water saturation in the microatmosphere of the sealed fruit.

Lemons are a crop that could benefit from curing (13, 16). Lemons reach marketable size in spring, but the peak market demand does not occur until mid- to late summer. Due to chilling injury sensitivity, lemons are stored at 13°C and 90% RH; however, these conditions do not maintain the quality of stored fruit throughout the summer (9). The main factors governing storage life of lemons are water loss and susceptibility to decay. Individual seal-packaging (3–5) could control water loss, and the potential risk for *Penicillium* decay of sealed fruit might be solved by curing.

The pomelo, compared with the lemon, is a better candidate for both curing and seal-packaging because the peel often is consumed and fruit are exported from Israel without any chemical treatment. The omission of a wax and fungicide treatment results in excess weight loss, lack of gloss, and an increased risk of decay.

The purpose of this study was to investigate the potential of curing of sealed lemons and pomelos and other citrus cultivars.

Materials and Methods

Citrus used in these studies were 'Eureka' and 'Villafranca' lemons, 'Goliath' pomelos, and 'Shamouti' and 'Valencia' oranges. Two selections of 'Villafranca' lemons were examined, a normal and a selection prone to green mold decay. Fruit were obtained directly from orchards or packing houses. Samples of fruit of uniform size and appearance, originating in one orchard, were subjected to different treatments at random.

High-density polyethylene (HDPE) film was applied with a plastic heating unit (Swery, Petach-Tikva, Israel) and later with specially designed sealing machines (4). The HDPE, supplied by Mitsui Petrochemicals, Japan, had a specific density of 0.955. It was extruded to make a sleeve or bag, in which the individual fruit was sealed and then shrunk in a hot-air tunnel that caused the film to adhere to the fruit. Seal-packaging also was carried out with a D-950 or MPD film (W.R. Grace, Cryovac Division).

Inoculations were made by piercing the flavedo to a depth of 1.5 mm with a needle on the equatorial plane of the fruit. The needle was immersed in a suspension of *P. digitatum* containing 5×10^6 spores/ml just before the inoculation. Each fruit was maintained for 24 hr after inoculation at 17°C and 85% RH to allow the pathogen to develop as expected within normal conditions between the harvest and the application of any decay control measures. Only then were the fruit transferred to the curing chamber, unless described otherwise. Control fruit were maintained in water-saturated conditions, achieved either by the Humifresh technique (16) or by holding fruit in a tray covered with plastic film. The sealed fruit could be cured at low humidities, since their microatmosphere is normally water-saturated. Nonsealed fruit were cured at constant high temperatures and a water-saturated atmosphere. Temperatures examined were between 25° to 42°C for durations of curing of 1 to 3 days.

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After curing the fruit were stored at 17° or at the optimum temperatures of 13° for lemons, 11° for pomelos, and 6° for 'Shamouti' oranges.

The following measurements were carried out with all sealed and nonsealed fruit: a) percentage of decay; b) weight loss; c) endogenous level of CO_2, O_2, ethylene, acetaldehyde, and ethanol and production of CO_2 and ethylene by methods described in previous reports (6, 8); d) external appearance; e) flavor (using a triangle test) (3, 4); and f) fruit firmness.

Experiments with lemons and pomelos included both inoculated and nontreated fruit. Each inoculated treatment had 25 fruit. The inoculations allowed rapid study of the effects of parameters, such as temperature of curing and its duration, on both the development of pathogen and phytotoxicity to fruit. Results were obtained 2 to 3 weeks after the beginning of experiments, although the observations in the early experiments were carried out for longer periods, in order to check the possibility of recurrence of decay or damage on cured fruit.

After the relevant parameters of curing were tentatively established, experiments were carried out with nontreated fruit. Each treatment included 100 fruit, and experiments were repeated for at least five times with each cultivar.

The composition of internal atmosphere and production of CO_2 and ethylene were determined from five fruit that were free of decay and blemishes. Each experiment was repeated three times.

Effects of Zivdar waxing were investigated using 'Shamouti' and 'Valencia' oranges with 100 fruit in each treatment.

Means were separated by Duncan's multiple range test for composition of CO_2 and ethylene on weight loss and on decay.

Results

Effects of curing on decay. Curing at optimal conditions reduced green mold decay of normal and the decay-prone 'Villafranca' lemons (Fig. 1). As expected, the decay-prone fruit rotted rapidly. One month after harvest, 45% of the nonsealed, decay-prone fruit developed decay, compared to only 12% of the normal fruit. Curing reduced decay drastically, to 2% and 4%, respectively. Inhibition was most evident in decay-prone fruit, where 73% of the sealed, noncured fruit rotted 2 weeks after harvest. In three experiments with normal fruit, seal-packaging did not increase green mold consistently as it did with the decay-prone fruit. Curing reduced green mold of pomelos in even more drastic fashion. Table 1 reports data with late-season (March) fruit, when decay was high. Curing prevented decay for 2 months, the period required for export to Europe; furthermore, curing reduced decay to 5% for 16 weeks, a period when the noncured fruit had 43% decay. The pathogen in both lemons and pomelos was *P. digitatum;* therefore, the inhibiting data refer only to the green mold.

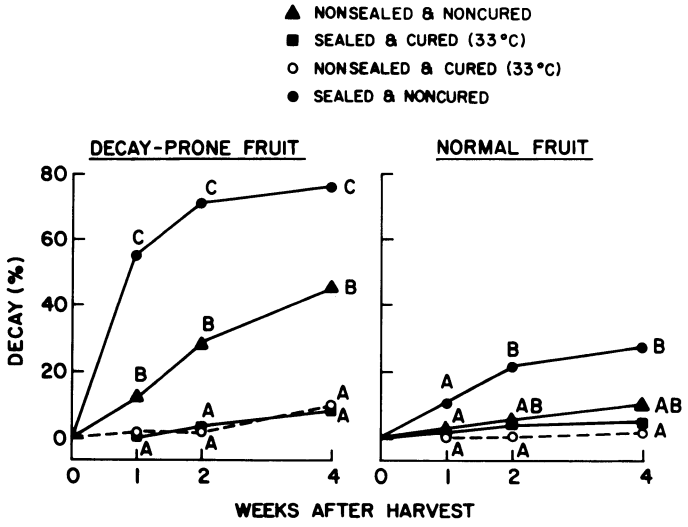

Fig. 1. Effect of curing on the percentage of green mold of decay-prone and normal 'Villafranca' lemons. The fruit were sealed with Cryovac D-950 film, 15 μm thick, which shrunk to the fruit in a heat tunnel. Fruit were held at 17°C after curing for 3 days at 33°. Mean separation within columns according to Duncan's multiple range test, $P = 5\%$.

Effects on inoculated fruits. The effectiveness of curing was increased on lemons inoculated with *P. digitatum* (Fig. 2). The control fruit held at 17°C developed 50% decay, as designed by the dosage of spores per milliliter of fungal suspension (1). Curing at 36° prevented the development of decay in both the sealed and nonsealed fruit. In these experiments, sealing, per se, whether with film of HDPE, Cryovac D-950, or Cryovac MPD, slightly inhibited the development of *Penicillium* decay even at 17°. The decay in nonsealed lemons cured at 30° increased in some experiments (reaching 72% rot); however, the sealed fruit cured at 30° had much less decay (Fig. 2) than noncured fruit.

Similar results also were obtained with pomelos. Decay of sealed and nonsealed fruit cured at 30°C was higher than that of noncured fruit or fruit cured at higher temperatures. Thus, 4 days after inoculation, at the end of the curing period at 30°, green mold decay of sealed and nonsealed pomelos was 66% and 60%, respectively, whereas inoculated fruit held at 17° had decay of 23% when sealed and 20% when nonsealed. At temperatures of 33°, decay did not develop at all. After 1 month at 30°, the inoculated fruit, both sealed and nonsealed, developed 100% decay, but at 17°, only 80%, and, at 33°, none.

Protection of fruit from high temperature damage by seal-packaging in plastic film. Individual seal-packaging in plastic film, such as HDPE, Cryovac D-950, or Cryovac MPD, protected the fruit from the damage incurred by high temperatures. The nonsealed fruit, kept at 33°C for 3 days, lost weight rapidly, shrank, and softened much faster than fruit kept at 17° or than sealed fruit kept at 33° (Fig. 3). For example, nonsealed fruit kept at 33° for the first 3 days followed by 29 days at 17° lost 12.6% of its original weight, whereas sealed fruit lost 3.1%. Weight loss of the decay-prone fruit was significantly higher than that of the normal fruit (Fig. 3). Sealing reduced weight loss to the extent that the difference between normal and decay-prone fruit was not noticeable.

Curing caused drying, shrinkage, and deformation of the non-

Table 1. Effects of a curing treatment on the percentage of green mold decay in sealed 'Goliath' pomelos kept at 11°C and 85% RH.

	Green mold decay (%)			
	Weeks at 11°C			
Treatment[z]	4	8	12	16
Nonsealed	3.1 B[y]	18.7 B	18.7 B	43.1 C
Sealed	6.5 B	20.6 B	22.3 B	25.4 B
Sealed in HDPE and cured	0 A	0 A	3.0 A	5.4 A

[z] Fruit were cured for 3 days at 36°C.

[y] Values within columns separated by Duncan's multiple range test, $P = 1\%$.

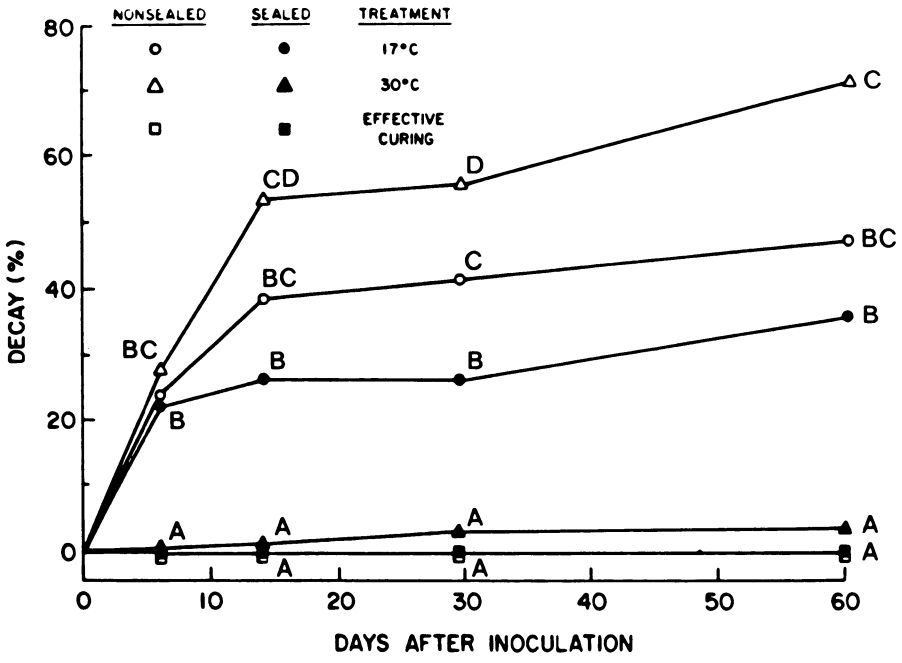

Fig. 2. Effect of curing 'Eureka' lemons for 3 days at various temperatures on the development of green mold of *Penicillium digitatum* inoculated with a suspension of spores on a needle inserted into the peel at a depth of 1.5 mm. Fruit either were sealed and shrunk in 10 μm HDPE or left nonsealed and held after curing at 17°C and 85% RH. Curing at this experiment was performed at 30° and 36° for 3 days. Mean separation within columns according to Duncan's multiple range test, $P = 5\%$.

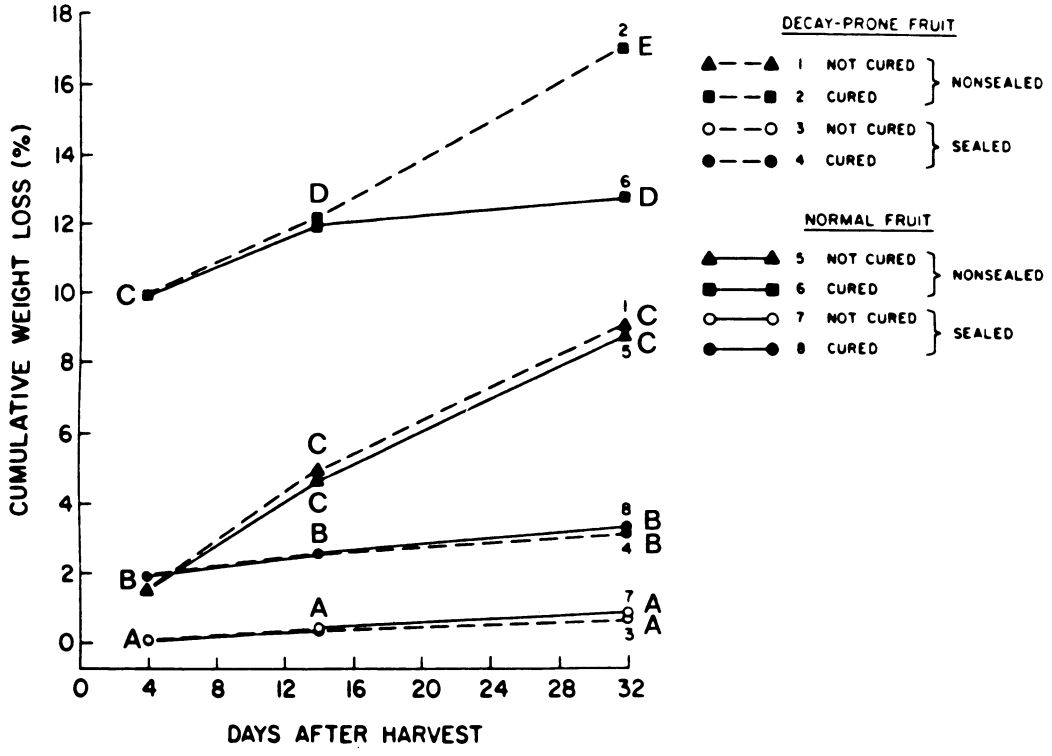

Fig. 3. Effect of curing at 33°C and sealing on weight loss of normal and decay-prone 'Villafranca' lemon fruit kept at 17°. Mean separation within columns according to Duncan's multiple range test, $P = 1\%$.

sealed fruit that could not be tolerated commercially (Fig. 4). Sealing inhibited softening. After a curing treatment of 3 days at 36°C, only the nonsealed cured lemons had started to soften, but all other treatments—the nonsealed, noncured fruit and the sealed, cured fruit—were still firm and fresh. Similar results were obtained with pomelos. The cured lemons or pomelos remained firm for 6 months.

Protection from heat by sealing the fruit was evident only up to a certain temperature (≈38°C), above which the sealed fruit evinced more damage than the nonsealed (Fig. 4). This critical temperature appears different for different cultivars. Cells of the sealed and cured lemons at 42° exploded; the fruit segments had cracks inside, similar to those of frozen fruit (19). The fruit that developed this symptom also lost much of its juice, appeared dry, and was inedible, similar to fruit that show granulation (19). Cracking at the 42° treatment became visible only 12 days after the termination of the curing treatment.

Effect of curing on flavor. Flavor of pomelo and orange fruits

and of juice of both lemons and pomelos was normal. Six weeks after harvest, a taste panel of 20 skilled people could not identify cured from noncured fruit. However, after 4 months at 11°C, this panel preferred the cured over the noncured fruit.

Effect of curing on composition of internal atmosphere and production of CO_2 and ethylene. The curing treatment, as expected, altered the composition of the internal atmosphere of both 'Villafranca' lemons (Table 2) and 'Shamouti' oranges (Table 3). The contents of CO_2 and ethylene rose and that of O_2 declined significantly at the end of the curing treatment. One month after the curing treatment, the difference in the composition between cured and noncured lemons disappeared. The respiratory activity, as measured by CO_2 production, increased after curing but also later subsided (Table 2). Ethylene production also was raised by curing, but not significantly with lemons (Table 2). However, ethylene content of both lemons and 'Shamouti' oranges (Tables 2 and 3) was significantly increased by curing. Sealing, per se, did not alter the composition of the noncured fruit, as reported previously for lemons (8) and other citrus fruits (4).

The curing of waxed 'Shamouti' oranges altered the composition of the internal atmosphere excessively. Table 3 shows that the internal CO_2 and O_2 reached an equilibrium around 10% of each gas. This atmosphere is known to be toxic to citrus fruit (20) and, indeed, CO_2 injury was seen as brown patches on the peel of 5% of the fruit (Fig. 4). Few of the waxed sealed and cured 'Shamouti' and 'Valencia', but none of the nonwaxed sealed and cured fruit, developed off-flavor.

Waxing increased the risk of damage by high temperature. Thus, nonwaxed sealed 'Valencia' oranges could bear a temperature of 36°C, but waxed 'Valencia' was injured even at 33°. Waxed sealed and cured 'Valencia' had 16% fruit with light blemishes and 3% with severe damage (commercial cull).

Discussion

Curing of sealed 'Villafranca' and 'Eureka' lemons and 'Goliath' pomelos reduced decay without any deleterious effects on appearance and flavor and reduced the development of green mold decay caused by *P. digitatum* on lemon and pomelo fruits. Sealing of fruit markedly improved the effects of curing. Although curing could, at certain temperatures, reduce green mold of nonsealed fruit, such fruit were excessively heat-damaged and lost their commercial value. Seal-packaging apparently provided the water-saturated atmosphere required for successful curing and mitigated the disadvantages of a water-saturated treatment room (4, 5, 8). Visually the sealed fruit had fewer water droplets on its surface than the nonsealed fruit at water-saturated atmosphere. Furthermore, the marked reduction of heat damage also was seen in the practical elimination of shrinkage and softening of the sealed fruit. It is interesting that the combined effect of sealing and the exposure to relatively high temperatures did not affect the flavor of fruit and altered its internal atmosphere only to a small extent and for a temporary duration. However, the combination of three factors—waxing, sealing, and curing at high temperatures—caused both CO_2 injury and off-flavor in 'Shamouti' fruit. Ben-Yehoshua et al. (6) have shown that waxing has a greater effect in impeding gas exchange than does seal-packaging. It is possible, but not yet established, that curing of some citrus fruit may not be compatible with waxing.

The more drastic effects of curing on the production of CO_2 than on ethylene could be explained by the greater sensitivity of the ethylene production system than that of the respiratory apparatus to high temperature. The same explanation could be related to the significant effect of curing on the content of ethylene than on its production (Table 2).

Curing may be used with seal-packaging citrus fruit to reduce decay; however, much work still is required to optimize the conditions or improve curing. These encouraging results should be considered along with the findings that important pathogens of citrus fruit (i.e., *D. natalensis* and *G. candidum*) appeared resistant to temperature and kept growing at 30°C; the former even maintained growth at 40° (9).

The curing of sealed pomelos provides the means for decay control without chemical and toxic residues. Additionally, the seal-packaging controls weight loss, provides the gloss of the plastic film, delays fruit deterioration, and allows easy brand marking.

The heat damage incurred at 42°C for lemons relates well with the thermally induced destruction of membranes of disks of beet (*Beta vulgaris* L.) roots (22).

The exact mode of action of curing in reducing decay is not understood. However, two factors can be mentioned. First, seal-packaging, as well as a water-saturated atmosphere, were demonstrated to delay senescence and maintain the integrity of cellular membranes (8). Furthermore, sealing, as well as a water-saturated atmosphere, were shown to accelerate healing of various peel injuries (4, 5, 15) and to reduce peel blemishes (7, 9) on both citrus and tomato fruits. Second, several investigators have demonstrated that wounds in the flavedo of citrus peel develop resistance to infection by *P. digitatum* when the fruit are held at a high humidity and warm temperature (20° to 30°C) (2, 10). Under these conditions, the activity of phenylalanine-ammonium lyase increases (12, 15) and phenolic materials ac-

Table 2. Effect of curing on the composition of the internal atmosphere of 'Villafranca' lemon fruit.

Treatment	CO_2 (%)	O_2 (%)	Ethylene (μl·liter)	Respiration (ml CO_2/ kg per hr)	Ethylene production ($\mu l \cdot kg^{-1} \cdot hr^{-1}$)
			Sampling at the end of curing		
Cured	3.1 A[y]	17.7 A	0.481 A	10.8 A	0.06 A
Noncured	1.1 B	19.7 B	0.134 B	4.3 B	0.04 A
			Sampling after 1 month at 17°C		
Cured	1.4 B	18.8 B	0.109 B	3.0 A	0.03 A
Noncured	1.7 B	19.7 B	0.110 B	2.8 A	0.03 A

[z] Fruit were cured at 33°C for 3 days. Curing applied 24 hr after harvest. Waxing and disinfection were not applied.
[y] Differences between cured and noncured separated by Duncan's multiple range test, $P = 1\%$.

Table 3. Effect of curing on the composition of the internal atmosphere of 'Shamouti' oranges.

Curing[z]	Sealed in Cryovac D-950 film	CO_2 (%)	O_2 (%)	C_2H_4 ($\mu l \cdot liter^{-1}$)	Ethanol ($\mu l \cdot liter^{-1}$)	Acetaldehyde ($\mu l \cdot liter^{-1}$)
−	−	5.1 A[y]	17.8 A	0.140 A	1301.0 A	24.1 A
−	+	4.2 A	15.1 A	0.220 A	1345.5 A	21.1 A
+	−	8.2 B	10.1 B	0.760 B	3281.0 B	31.4 AB
+	+	10.2 B	6.7 B	1.300 B	4161.3 B	54.1 B

[z] Fruit were treated and waxed in the packing house, cured at 36°C for 3 days, and the internal atmosphere was measured after 2 days at 17° and 85% RH.

[y] Within columns, values separated by Duncan's multiple range rest, $P = 1\%$.

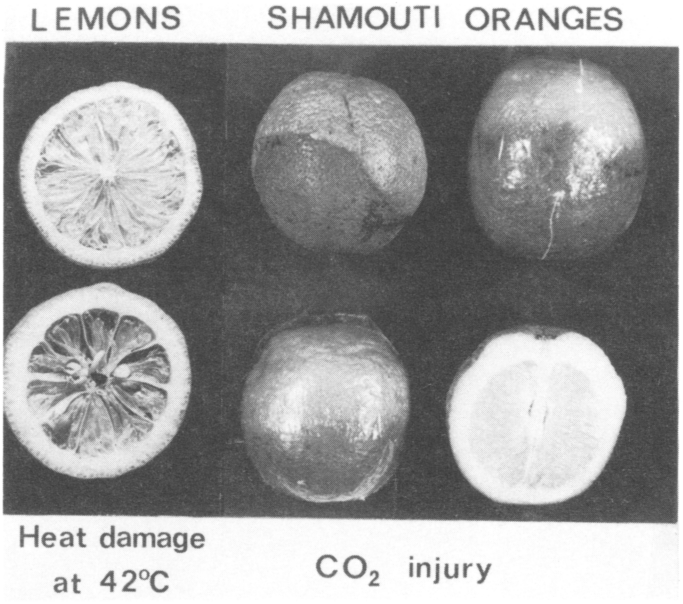

Fig. 4. Heat damage to lemons cured at 42°C and CO_2 injury to 'Shamouti' oranges cured at 36°.

cumulate in the injured flavedo tissue (18). Resistance of injured citrus rind to invasion by *Penicillium* appears to be due to the accumulation of phenolic- and lignin-like materials in the cell wall of damaged tissues (12, 18). These materials may prevent penetration of the germinating spores into the flavedo tissue or interfere with the action of pectolytic enzymes of the pathogen (2, 11, 13).

Ben-Yehoshua et al. (9) have found that antifungal materials, such as scoparone and umbelliferone, could be isolated from cured fruits.

Recently, Afek et al. (1) have isolated scoparone from bark of citrus trunks inoculated with the fungus *Phytophthora citrophthora*. They also showed that scoparone inhibited the growth of this fungus. Accordingly, they have proposed that scoparone is the natural phytoalexin responsible for the defense mechanism against *P. citrophthora* in citrus.

If curing could achieve disease control by itself, as demonstrated in this work for pomelos, it would be most useful because it would enable production of a residue-free fruit. Such would have a world-wide market because of the ever-growing fear of toxic residues. However, a more pragmatic view (and still optimistic) considers curing as an additional supporting means in the arsenal of weapons available to protect fruit from decay and to heal mechanical damage.

The special case of decay-prone lemons may help in analyzing the mode of action of curing. So far, the only parameter that was different in this decay-prone fruit from the normal was its rate of weight loss. The significantly greater weight loss of this sensitive fruit compared with the normal lemon may be caused by injury. It is well-known that injured fruits lose weight at a rate much higher than noninjured fruit (5, 16). Such an injury indeed may explain the sensitivity of the fruit to decay, as well as the capacity of the curing treatment to reduce this sensitivity, probably both by healing injury (10) and by inhibiting development of decay (10, 17).

Finally, the relatively high percentage of decay of lemons generally, and of sealed fruits specifically (Fig. 1), is related to the lack of decay control in these experiments. Generally, sealed lemons have less decay than those nonsealed.

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Firmness of Tomato Fruit Tissues According to Cultivar and Ripeness

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Additional index words. *Lycopersicon esculentum*, pericarp, placenta, maturity

Abstract. **The firmness of tissues of a transverse equatorial slice of fruits of 'Flora-Dade', 'Walter', 'MH-1', and 'Homestead 24' tomatoes (*Lycopersicon esculentum* Mill.) was determined at different stages of ripeness by use of an Instron Food Testing System. The outer, radial, and inner pericarp tissues of 'Flora-Dade' and 'MH-1' were firmer than those of 'Walter' when ripened 6, 8, or 10 days at 20°C after incipient color formation. 'Walter' tissues were intermediate in firmness between 'MH-1' and 'Flora-Dade' at the mature green stage, but had softened much more than either at the incipient color stage. Most of the softening of the tissues of the three cultivars had occurred by 4 days after incipient color. The placental tissue of 'Homestead 24' fruit was much firmer than that of 'Walter' and 'Flora-Dade' over a period of 7 to 19 days after incipient color stage, although the outer pericarp tissue was much softer than that of the latter two.**

Firmness is an important attribute of tomato quality. A number of instruments have been used to measure firmness of tomatoes (1, 2, 11, 14, 16) based on the compression of whole fruits, either at a single point or surface (11) or by compression of the total equatorial circumference (14). These types of instruments measure the overall firmness but do not determine the firmness of individual fruit tissues. In studies on the relationship of cell wall constituents to firmness, tissue firmness should be determined rather than overall fruit firmness. Foda (4) used this approach with the Illinois Pressure Tester devised by McCollum (15). The large plunger diameter (1.25 cm) restricted its use to inner pericarp tissue of a median slice. Holt (12) measured firmness of different tissues by driving a 1.02-mm-diameter plunger tip into fruit through the skin using an Instron Universal Tester. The penetrated tissues were determined by dissecting the fruit.

In this study, firmness of the pericarp wall tissues of a transverse slice was determined for several cultivars at various stages of ripeness.

Materials and Methods

Plants were grown in 22.5-cm black plastic pots filled with a commercial Vermiculite–peat mix in a greenhouse equipped with cooling pads and fans. The plants were fertilized with a 12N–10P–20K soluble mixture containing Ca, Mn, and minor elements. Plants for the first three tests were grown in the spring with harvests in May and early June when the temperature ranged from 20° to 35°C. Plants for the last two tests were grown in the fall with harvests in December and January when temperatures ranged from 15° to 27°.

Fruit were picked at the mature-green stage and placed at 20°C and 85% RH. Fruit showing incipient color on the stylar end (15) were assigned at random to the treatments and held under the same conditions.

Fruit tissue firmness was measured with an Instron Food Testing System (Model 1132) machine fitted with a 2-kg compression load cell. The machine was calibrated to give full deflection for a 1-kg weight. Crosshead and chart speeds were 5 $cm \cdot min^{-1}$. A 1.25-cm-thick transverse slice, taken by use of two attached blades, midway between the stylar and stem ends was placed on a stainless steel plate with proximal side up. A cylindrical probe, 4.9 mm in diameter, with a flat surface was made to penetrate 5 mm into the tissue. Three readings were taken for each tissue on each slice. The peak heights of each three readings were averaged and converted to newtons (13). The designations of the fruit tissues are as given by Davies and Hobson (3).

In the first test, the firmness of the outer pericarp (opposite the locules), the radial pericarp, and the inner pericarp (columella) was determined with fruit ripened 6 days using 'MH-1', 'Flora-Dade', and 'Walter'.

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