DETECTION SYSTEMS, PHYSICAL PROPERTIES AND STORAGE STABILITY OF APPLES AFFECTED WITH WATERCORE DISORDER[1]

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FINAL REPORT

TO

Dr. Bruce Upchurch,
USDA-ARS Applachian Fruit Research Station
Kerneysville, West Virginia

FOR

SPECIFIC COOPERATIVE AGREEMENT

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entitled

EFFECTS OF STROAGE TIME ON SEVERITY OF APPLE WATERCORE DISORDER

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EXECUTIVE SUMMARY

Instrumentation systems (X-ray detection and visible light transmission) were evaluated for nondestructive detection of watercore disorder and alternative storage techniques were evaluated for minimizing the impact of watercore on stored apples. Destructive physical property measurements (Density, water content) and visual evaluations of cut fruits were also made and formed the basis for evaluating the technologies as well as storage alternatives.

X-ray computed tomography (CT) was used to image interior regions of Red Delicious apples under varying moisture and, to a limited extent, density states. Images were actually maps of x-ray absorption of fruit cross-sections. X-ray absorption properties of Red Delicious apples were evaluated using normal apples alternately scanned and sequentially freeze dried, fruit affected by watercore disorder, and normal apples freeze-dried to varying levels. The studies were designed to allow quantification of the x-ray absorption coefficient associated with the dry solids portion of the fruit and the x-ray absorption coefficient associated with moisture. The coefficients associated with moisture were in the vicinity of 0.0191 mm^{-1} and 0.0182 mm^{-1}, the expected value for water and ice respectively. The coefficient associated with the dry solids was not significant from zero, due in part to scanner resolution limits, limited dynamic range in density values, and to variation in the physical density measurements. The results of this study suggest that internal differences in x-ray absorption within scans of fruit cross-sections are largely associated with differences in

volumetric water content. Correlations between X-ray CT and visual observations approached 80% for the 1991 season when watercore disorder was widespread.

A machine vision system for quantifying light transmission was used for detecting watercore disorder in a storage study. Apples with watercore disorder were stored at either a refrigerated (1°C) or a controlled atmosphere (CA) condition (2% O_2 and 2% CO_2) for selected periods of time. There was no difference in light transmission score between apples stored at either refrigerated or CA condition for the first two weeks. Subsequently, light transmission scores for apples stored under the refrigerated condition decreased faster than apples stored under the CA condition. This indicates that apples with watercore disorder may not be appropriated to store under a CA condition.

Apples with severe watercore disorder were more dense than apples with mild or no watercore disorder. Moisture content of affected tissue from apples with severe watercore disorder was significantly higher than tissue from apples with a mild disorder. Apples stored under the refrigerated condition lost more weight (4.4%) than apples stored under the CA condition (1.8%). Apples stored under the refrigerated condition had less severe watercore disorder after storage (severity score = 1.69) than apples stored under the CA condition (severity score = 2.42).

INTRODUCTION

Watercore is a physiological disorder in apples. It has consistently been considered as a serious problem in the United States (Fisher, 1923; Lord and Damon, 1966; Simons, 1968). If affected apples are stored for any length of time, anaerobiosis and subsequent tissue breakdown become a problem (Smagula et al., 1968).

Damage by watercore in the United States Standards Grade of Apples (USDA, 1976) "means externally invisible watercore existing around the core and extending to the vascular bundles; or surrounding the vascular bundles when the affected areas surrounding three or more vascular bundles meet or coalesce; or existing in more than slight degree outside the circular area formed by the vascular bundles; or any externally visible watercore." Detection of watercore in apples is important because watercore can develop internal browning that leads to breakdown of the tissue and causes a downgrading of the entire batch. The breakdown of watercore tissue in storage is another source of potential loss to the grower if fruit with watercore disorder is unknowingly placed in the refrigerated storage. The storage cost of useless fruit contributes to potential economic loss to the grower (Throop et al., 1989).

Detection of apples with watercore disorder non-destructively can prevent downgrading the rest of the apples. Apples with minor watercore disorder can still be sold immediately to the market before the tissue breakdown occurred. However, watercore affected apples are not visually detectable for the whole fruit (Morlow and loescher, 1984). To develop a

INTRODUCTION

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[illegible] apples with watercore disorder [illegible] by [illegible] downgrading the rest of the apples [illegible] watercore disorder can still be [illegible] before the tissue breakdown occurred. [illegible] a not visually det[illegible] non-destructive detection method; understanding the chemical, physical, and structural differences between watercore affected and un-affected apples are important. There were several analytical comparisons between affected and un-affected apples and between affected and un-affected tissues within the same apple and these information have been summarized by Marlow and Loescher (1984). Generally, watercore affected apples have a high water content, more anaerobic products, high sorbitol content and a lower reducing sugars than un-affected apples.

Fidler et al. (1973) reported that as watercore develops, the specific gravity of affected apples approached the specific gravity of cytoplasm (specific gravity of 1.10). This property has been utilized to remove apples with watercore disorder by a flotation method (Porritt et al., 1963). However, smaller apples tended to be more dense so different flotation solutions are needed for different size of apples (Fidler et al., 1973).

Normal apples have 20-35% of the total tissue volume occupied by the intercellular air space, whereas in apples with watercore disorder this large air space is filled with a liquid (Marlow and Loescher, 1984). This liquid reduces the light-scattering ability of the tissue and cause apple to appear more translucent than normal (Olson et al., 1962; Throop et al., 1989). Throop et al. (1989) used computer vision to quantify light transmission through apples, viewed from the stem-end, as an indicator of watercore. However, the method was not accurate enough to determine the degree of watercore severity. Upchurch and Throop (1991) further revised the machine vision system for classifying the fruit into four degrees of watercore severity.

They found system performance was dependent upon sensitivity of the camera. A more sensitive camera distinguished differences among the less severe classes, while a less sensitive camera successfully segregated only the more severe classes of watercore damage.

Researchers have reported that mild watercore will diminish during storage while severely watercore-affected fruit will experience internal breakdown (Marlow and Loescher, 1984, Myers, 1983). Upchurch and Throop (1991) reported that 63 apples had an initial mean light transmission level of 1.0 or higher (severe watercore); however, after 14 weeks of refrigerated storage internal rotting occurred only in three apples while internal browning was present in seven apples. The other 53 apples showed no signs of watercore.

There is no agreement on which storage conditions will effect this process the most. Some have suggested higher temperature be more effective (Schomer, 1955; Fidler et al., 1973); others have suggested cooler temperatures (Anderson, 1956; Perring, 1971), and Cunningham (1925) has favored ambient temperatures followed by a cold storage. It is also not clear whether only the symptoms disappear or whether the conditions causing watercore disappear as well. There is also no consensus on the effects of controlled atmosphere (CA) on watercore disorder. Smock (1977) reported that CA would delay the onset of watercore breakdown whereas Bartram (1965) stated it may be detrimental. Improved techniques for nondestructively observing changes inside an individual fruit would increase accuracy of data collected and reduce sample sizes required for scientific

experiments. Sorting operations at packinghouses may be more accurate if internal quality could be evaluated nondestructively on an individual-fruit basis. Presently, destructive tests are the predominant method for evaluating internal quality characteristics of fruits.

Direct transmission approaches such as x-rays, optical energy or ultrasonic methods can be useful for evaluating internal quality of several food products. However, the resulting information from these techniques is unsatisfactory for analyzing specific locations of a fruit because of inherent volume averaging effects. X-ray computed tomography (x-ray CT) imaging is a proven method for nondestructively evaluating a cross-section of an object. CT greatly reduces volume averaging. Each point on a CT image represents a small volume in the plane scanned by the x-ray system, while a point on a transmission x-ray image (film) represents a volume average of many volume elements between the x-ray source and the film. The application of x-ray CT for quantifying physical properties of fleshy fruits requires appropriate correlations between the physical property and x-ray absorption. These correlations would enable the use of x-ray CT to nondestructively quantify physical properties of food products.

A major difficulty in correlating CT measured absorption values to physical products is that in most cases the accepted measurement technique for physical properties such as moisture or density require considerably more sample than is represented by a single voxel by the scanner. A voxel is the smallest rectangular solid for which an x-ray absorption measurement is made by a CT

system. Thus, one must make correlation using a group of voxels. In order to use CT images to diagnose moisture distribution which may vary over relatively few pixels, one must in effect assume that mean absorption values for single pixels or small groups of pixels can be represented by mean absorption values for a large region such as an entire fruit cross section. This question was addressed by Tollner et al. (1989). They found that pixels as far as four pixels away were statistically independent. Pixels less than four pixels away showed significant correlation. Thus, it is felt that pixel groupings of at least four pixels-by-four pixels should yield stable mean values. They also noted that measured means from regions filled with water gave nearly the same value when surrounded by water or soil. This implies that regions at least four pixels-by-four pixels (4 mm x 4 mm) can be regarded as independent of surroundings in an image. Based on Tollner et al. (1989), it was concluded that calibration relations over a whole fruit cross-section can be applied to small subregions in the fruit to further interpret the image. Volume averaging over the cross section also implies linear relations between x-ray absorption and the physical properties. This assumption was found to be valid for soil-water systems (Tollner and Murphy, 1991). X-rays have been used in the food processing industry for several years. Schatzki et al. (1981) demonstrated the technique for determining the density of lettuce heads prior to harvesting. In food processing plants, x-ray based technologies have successfully detected stones, bones, metal and other objects (Gerber et al., 1985). Diener et al. (1970) and Ziegler and Morrow (1970) demonstrated that x-ray

transmission through bruised apple tissue was less than the transmission through non-bruised tissue. The type of bruise was not clearly specified. X-ray technology has been useful in quantifying lettuce maturity (Garrett and Lenker, 1976). Transmission x-rays are currently used by some commercial operations, particularly in the on-line detection of freeze-damaged citrus (Bilton, 1991). Garrett and Lenker (1976) discussed direct transmission x-ray absorption processes relevant to food materials.

X-ray computed tomography (x-ray CT) allows one to characterize relative x-ray absorption properties of solid objects with much greater detail than is possible with conventional x-ray approaches. Scanners measure relative x-ray absorption of many small volumes known as voxels, which comprise the scanned region. The CT scanning process is shown in simplified terms in Figure 1. During scanning, data from many collimated x-ray beams are collected over many different paths through the object of interest, which is placed in the scanner bore. The "as viewed" disk in Figure 1 represents the scanned disk into pixel-sized display units with length and width (LxW) and shown with an intensity corresponding to the absorption of voxels (LxWxD) of material in the scanned plane. Typical voxel dimensions (LxWxD) are 1x1x13 mm. The length and width (L, W) are measured in the plane of the "as viewed" section and are determined by scanner software from operator selectable options. The depth (D) is set by the thickness of the collimated x-ray beam. Possible depth values are 5, 8 or 13 mm on our system, as shown in Figure 1. Scanner systems typically display images

comprising pixels from the scanned region. Pixel dimensions are mapped from the LxW voxel dimensions and the pixel intensity is related to x-ray absorption in the voxel. Herman (1980) gives detailed discussions of x-ray CT scanner reconstruction algorithms. It is interesting to note that summation of individual voxel absorption values along vertical transects would result in the equivalent of transmission radiography at a point. Thus, one can immediately appreciate the increased resolution available with x-ray CT.

CT systems, following precedents set by the medical community, report absorption values in terms of Hounsfield (H) units. By definition, the absorption value for water is zero Hounsfield. The value for air may range from -500 H to -1000 H or lower, depending on the particular CT system. Older systems use the value of -500 H for air, while newer systems range from -1000 H or lower. Later systems have increased capability to precisely measure lower absorption values.

Tollner and Murphy (1991) discuss the physics of x-ray absorption with CT scanners at length. The x-ray source in a CT scanner is polychromatic, with the average wavelength typically centered around 1×10^{-10} mm. Absorption values are therefore to be considered in a nominal sense. Scanners are typically calibrated using air and water standards. Nominal absorption of air is zero mm^{-1} and the value for water is 0.0191 mm^{-1}. Using the value for air of -500 H (which it is for the EMI 5005 available in our lab), the following relationship can be used to relate Hounsfield (H) values to nominal absorption (μ, mm^{-1}):

$$\mu = ((H + 500)/500) * 0.0191 \qquad [1$$

Potential value of CT scanners in agricultural research arises from the possibility of relating nominal absorption to the physical properties of moisture and density using the linear relationship in Equation 2 (Tollner and Murphy, 1991).

$$\mu \quad = \quad (A * \theta) + (B * \rho_b/\rho_t) + C \qquad [2$$

where θ = volumetric water fraction (mm^3water per mm^3 bulk fruit)
ρ_b = dry bulk density (Mg/m^{-3})
ρ_t = dry tissue density (Mg/m^{-3})
A, B = absorption coefficients to be determined (mm^{-1})
C = intercept (mm^{-1})

Volume of water in the apple is computed by multiplying gravimetric moisture (wet or dry basis) times the (wet or dry) bulk density and dividing by the density of water. The dry bulk density ρ_b is the mass of bulk fruit per unit volume of bulk fruit. Tissue density ρ_t is the mass of bulk fruit divided by the volume of solid materials as measured by devices such as an air comparison pycnometer. Note that ρ_b/ρ_t can be expanded as $[\rho_{WB}(1\text{-}MCWB)]/\rho_t$ where ρ_{WB} is wet bulk density and MCWB is the gravimetric water content, wet basis. Also note that θ can be written as $MCWB*\rho_{WB}/\rho_w$, where ρ_w is the density of water. The value of coefficients A and B give the relative influence of moisture or solid material on the x-ray absorption measurement. Anderson and Gantzler (1987) and Tollner and Murphy (1991) found that the water term (A) approached the expected value of 0.0191 mm^{-1} with a variety of soils. Tollner and Murphy (1991) presented a relationship, given in Equation 3, showing that the

solids and water terms (A and B) is affected by the constituent electron density.

$$\frac{\mu_s}{\mu_w} = P_{SG} \frac{Z_S^3 \lambda_S^3}{Z_W^3 \lambda_S^3} \qquad [3$$

where P_{SG} = specific density of solid particles (Mg/m^3)

λ_S, λ_W = effective x-ray wavelength for solids and water (m). (λ_S is theoretically equal to λ_W.)

Z_S, Z_W = effective atomic number of solids and water.

The polychromatic nature of the x-rays creates interactions causing some difficulties in predicting values for one coefficient, knowing the other, particularly if one is working with dense material. In the case of fruits, the limitation should not be a problem. If one assumes a fruit solids composition of the form $C_nH_{2n}O_n$, then one would expect a value in the vicinity of that for water (H_2O) for the solids coefficient. Carbon has a lower atomic number than oxygen (6 versus 8), thus the coefficient should be somewhat lower since the effective atomic number is slightly lower compared to water. The intercept C is theoretically zero and usually approaches zero.

The overall objective of the project was to identify potential instrumentation systems for removing watercore affected fruits from the storage-bound stream at harvest and to evaluate specific alternatives for storing fruits to minimize the impact of watercore presence in the storage environment. Specific objectives of this study were: 1) to develop a general approach for correlating moisture and density measurements with x-ray

absorption measurements using fleshy fruits; and, 2) to evaluate the physical properties and stability of watercore affected apples in both refrigerated and CA environments.

MATERIALS AND METHODS

X-ray studies Experimental Materials

Red Delicious apples obtained from the USDA Appalachian Fruit Research Station were sampled for density, CT scanned, freeze-dried to varying moisture contents and rescanned in order to determine x-ray absorption/moisture-density relationships. The apples had been harvested approximately two to three months in each of the two years (1988; 1989). Mean x-ray absorption measurements were made on apples affected with mild to severe watercore disorder, motivated by the idea that watercore disorder may cause variation in density and moisture. The watercore disorder is a physiological disorder in which intercellular air space is filled with fluid (Throop et al., 1988). The degree of intercellular filling ranges from near zero (low watercore severity) to near maximum (severe watercore). Thus, it was anticipated that x-ray absorption coefficient associated with liquid and possibly solids could be measured from watercore affected fruit. For fruit evaluated in 1988, the wet bulk density of 40 fruits were measured on a whole fruit basis. Fruits were then scanned along a plane normal to the stem-calyx axis near the center of each fruit. Moisture measurements were then made on portions of the fruit. In fruit evaluated in 1989, a similar protocol was followed using 40 fruits. The experiment conducted in 1989 was modified by measuring wet bulk density and

tissue density on fruit segments made from the CT scanned plane instead of randomly over the entire fruit.

Drying experiments were designed in order to obtain a wider range of moisture levels compared to that available with watercore apples. Drying sequences using freeze drying were performed on the apples using variable interval drying/scanning on separate fruit and repeated drying/scanning of the same fruit. Freeze drying was used in an attempt to minimize bulk volume changes. Freeze drying also accelerated the drying process in order to minimize fruit deterioration. Fruit affected with watercore disorder were also evaluated without removing any moisture. Experimental conditions and selected data ranges are shown in Table 1.

The repeated interval drying experiments both involved: density measurements on whole fruit, slicing a 13-mm slice in the center of the fruit perpendicular to the stem-calyx axis, weighing the slice, scanning in the fresh state, freeze drying for 24 hours, reweighing and rescanning. The fruits were then dried for another 24 h and reweighed and rescanned. The weighing and scanning continued at 24 h increments until cumulative drying totaled 72 h. At the end of 72 h, the slice dry weight and final moisture content values were determined. Moisture content at other drying times were back-calculated using the slice weight measurements. Four replications were measured.

The variable interval (A) drying experiment involved the following steps: bulk density measurements on whole fruit, slicing a 13-mm slice in the center of the fruit normal to the stem-calyx axis, tissue density measurement on samples from

remaining fruit, freeze drying for 0 to 96 h at 24 h increments, scanning in the frozen state and subsequent scanning in the thawed state, then measuring resulting moisture content of respective slices. Four replications were measured.

Variable interval (B) was conducted similar to variable interval (A), except that bulk density and tissue density measurements were made on each scanned fruit piece after scanning that piece instead of prior to scanning. This would account for the (usually minor) changes to density during freeze drying.

X-ray studies Measurement Procedure

Moisture levels (percent wet basis) were determined using AOAC (1984) procedures. Wet bulk density was measured on whole fruits using procedures of Heaton et al. (1982) as modified by Chinnan (1988). Volumetric moisture was computed by multiplying the wet basis gravimetric moisture content by the wet basis bulk density. Dry bulk density was also computed by subtracting volumetric moisture from wet bulk density. Tissue density was measured using a Micrometrics Helium Pycnometer (Norcross,GA 30093).

X-ray CT scans were made using the Georgia Station EMI 5005 scanner operated at 120 kV, 700 mA*s. A 320x320 pixel density was used, resulting in 1.07 mm x 1.07 mm image pixels. Collimation was set at 8 mm. Fruit test sections were supported in the scanner using the support device (jig) shown in Figure 2 for scanning whole fruit. The jig shown in Figure 3 was used for scanning fruit slices. The latter support device had reservoirs for dry ice, enabling maintenance of frozen conditions when desired. X-ray absorption means for image regions representing

fruit segments in images were obtained using options available on the scanner. Each mean was based on averages of appropriate pixel groups representing the fruit in each image. Conversion was made from customary Hounsfield (H) units to units of absorption using Equation 1.

Response surface regression techniques and software of Hintz (1987) were used to analyze the data for coefficients A, B and C in Equation 2, following computation of the solids ratio term and the volumetric water term. Independent variables were volumetric moisture and density ratio and the dependent variable was mean x-ray absorption. The software tested the significance of linear, quadratic and cross-product terms enabling a more complete evaluation of adequacy. The software enabled separation of effects related to lack-of-model-fit and experimental error. Regressions were run with and without intercepts. Regressions were also run in which the moisture term was fixed, based on known values and a solids coefficient estimated.

Physical Properties Evaluation

Apples used for this study were "Red Delicious" apples handpicked in 1988 from the orchards of both Cornell and Washington State Universities and in 1989 from the USDA Appalachian Fruit Research Station. Approximately 10 apples for each watercore severity category based on the light transmission scores were used for the physical properties evaluation. They were shipped to the University of Georgia Experiment Station located in Griffin, Georgia in tray boxes through an overnight delivery service. Apples were stored in a 1 C cooler until used.

Moisture content of apple tissue was determined by the AOAC vacuum oven method (AOAC, 1984). Wet basis bulk density was determined for whole apple and apple tissue using the volume displacement principle described by Heaton et al. (1982). In stead of mustard seed, glass beads (Delong Equipment C., Atlanta, GA) were used. To alleviate the void space during filling, the set up developed by Chinnan et al. (1988) was adopted.

Storage Study-Light Transmission

Apples used for the storage study were also "Red Delicious" apples handpicked in 1991 from the orchard of the USDA Appalachian Fruit Research Station. They were categorized into watercore severity levels ranging from 0-4 (Throop et al., 1989) and then shipped to the University of Georgia Experiment Station located in Griffin, Georgia in tray boxes through an overnight delivery service. On arrival at the Georgia Experiment Station, fruits were scanned by light transmission; this value was used as the initial light transmission property.

A total of 44 apples without watercore disorder (unaffected) and 132 apples with watercore disorder (affected) were used for the storage study. Half the fruits from each group were placed in a cooler at 1 C; the other half was placed in a controlled atmosphere (CA) storage condition at 1 C. For the CA storage, apples were placed on paper trays (3 apples/tray) and each tray was sealed into a CURLON^R (Grade 863; Curwood, Inc., New London, WI) oxygen barrier plastic bag with a gas-exchange port. Bags were then filled with a gas mixture composed of 2% CO_2, 2% O_2 and 96% N_2. The filling procedure using a gas-exchange port was described in details by Hao and Brackett (1992). The [illegible] Collier et al. [illegible]

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only difference was that a flask containing water was connected between the gas tank and Firestone valve to bring the humidity of the mixture gas in each bag close to 100%.

Gas compositions in the bags were monitored every other day using a Hewlett Packard 5790 series gas chromatograph (Hewlett Packard, Avondale, PA) equipped with a thermal conductivity detector (temperature set at 250 C) and an Alltech CTR I column (Alltech, Deerfield, IL). Injector and oven temperature were 100 and 70 C, respectively. Helium (60 ml/min) was used as the carrier gas. Bags were re-flushed if gas varied from initial concentration by more than 1%.

Apples were sampled 2, 4, 6, 8, 12, 16, 20, and 24 weeks into the study. Each time all apples' weight, size and light transmission images were taken. One un-affected and three affected apples were destructively evaluated for visual watercore severity following the method given in Throop et al. (1989). The moisture content of both affected and un-affected tissues was determined following a vacuum oven method (AOAC, 1984).

Light transmission assessment was made using an adaptation of approaches presented in Birth and Norris (1965). Apples were positioned with the stem-calyx axis collinear to a 150 watts incandescent light source. Transmitted light was measured using a COHU CCD camera connected to a TARGA-M8 frame capture board mounted in a personal computer. Transmitted intensities were measured using standard image analysis techniques in a selected block of image pixels centered over the stem-calyx axis. The image analysis software was nearly identical to that in Throop et al. (1991).

Data were analyzed using GLM, Duncan's multiple range test and Student's t-test procedures of Statistical Analysis System (SAS, 1985).

RESULTS AND DISCUSSION

A CT image of a fresh apple from the repeated interval drying study is shown in Figure 4. The L and W indicators on the right side of Figure 4 indicate that the absorption thresholds in this image were at -100 H units extended to -200 H. In terms of nominal absorption, as defined in Equations 1 and 2, this corresponded to 0.0115-0.0153 mm^{-1}. A CT image of a slice of this same apple after 96 h of drying shows absorption in the .0077-.0115 mm^{-1} range (Figure 5). This absorption band width allows features of the wooden support jig to be visible in the image. Some cracking was apparent in the dried fruit images (Figure 5). These cracks resulted from the freeze drying procedure. Freeze drying did not eliminate all tissue shrinkage and associated cracking. The scanner software calculated the mean x-ray absorption for circular regions defined by inspection of images and this value was taken to represent the entire apple slice.

It was interesting to note that seeds were not visible in any image. Seeds were much smaller than the 13-mm beam thickness, resulting in volume averaging, which diminished possible effects of seeds on x-ray absorption. It has been observed that seeds of oranges[2] were less dense than surrounding

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[2] Unpublished data

liquid-filled tissue, suggesting potential low x-ray absorption by the seed portion in some fleshy fruits.

Models developed using linear regression for the various experiments are summarized in Table 2. Results of the 1989 watercore experiment were not shown due to the narrow range in moisture and density values observed. The lack of variation in moisture in the 1989 watercore study was surprising and disappointing in light of the care devoted to insuring proper handling of the slices. The 1988 fruits were stored for three months (10°C) before scanning, which may have contributed to a (beneficial) moisture range due to differences in moisture loss in individual fruit. In no instance was fruit observed to have shriveled. The ratio of dry bulk density to tissue density was not significant ($P \leq 0.05$) in any experiment except in the case of variable interval (A), frozen condition (Case 2B in Table 2). In most cases the density values varied over a very small range making the estimation of the solids term questionable. When fruit segments in the drying studies approached oven dry, the segment was barely visible under the best possible viewing conditions. Thus, the scanner resolution probably limited the capability to measure tissue density. It was assumed that freeze drying would not change the bulk density over time; however, comparison of Figures 3 and 4 indicated some shrinkage did occur during the drying process (particularly in the repeated interval study, where there were problems with the freeze dryer), which lead us to conclude that bulk density and perhaps particle density increased during the drying process.

Although moisture appears to be dominant in the relationship between mean x-ray absorption, moisture and density, a limiting case check applied to the models in Table 2 suggests that the solids fraction may indeed play a small role. For example, if moisture is 0%, the predicted mean x-ray absorption from all the equations exceeds the value for air defined for the EMI scanner to be 0 mm^{-1}. With several grain products the solids absorption coefficient was measured on oven-dried material (Tollner, unpublished data). After correction for bulk density and particle density the values were near those of water (0.014 mm^{-1}) compared to 0.0192 mm^{-1}. The low bulk density values with apples no doubt reduced the influence of the solids terms. The low density resulted in levels and changes which were near or below the noise level of the EMI scanner.

For three of the four models presented, the intercept appears to be significantly higher (based on intercept standard errors) than the value for air. Freeze-dried fruit at 0% moisture was barely visible in images, suggesting a small contribution from the solids. Also, if one set volumetric moisture fraction at 1.0 (implying a body of water) then the computed mean x-ray absorption should approach 0.0191 mm^{-1} (or 0.0182 mm^{-1} for ice). The value for each model representing thawed material is in the vicinity of 0.0191 mm^{-1}. Tollner and Murphy (1991) and Anderson and Gantzler (1987) found similar values for the water coefficient in several soils. The value for frozen material is close to 0.0182 mm^{-1} expected for ice. Running the variable interval modes forcing the intercept to zero

brings the coefficient closer to the expected values. The presence of the quadratic term in the repeated interval study is probably an artifact brought about by the assumption of constant wet bulk density of each slice over the course of drying. Thus, density should be monitored at each drying step. The linear equation in Table 2 suggests that one can safely use whole cross sections for calibration.

Results of these experiments suggest that volumetric moisture content is by far the most dominant factor determining x-ray absorption properties of apples; and by inference, other fleshy fruit. The results (except for the repeated interval study) also suggest that one could probably use the value of 0.0191 mm^{-1} for the water coefficient without an elaborate calibration. Recovery of values for the water coefficient in the vicinity of 0.0191 mm^{-1} in both apples and soils suggest a wide range of applicability for the water coefficient.

Based on measurements of slices with moisture contents approaching 0%, indications are that absorption of dry fruit flesh (at the density values associated with fruit flesh) is close to the lower limit possible on the EMI scanner. Better resolution of the solids coefficient may be obtained using more modern scanners which enable x-ray absorption measurements approaching 0.0001 mm^{-1}. Until new scanning equipment is available, inferences regarding relative differences within an image will be made related to volumetric water content as opposed to the ratio of dry bulk density to tissue density.

The results of this research suggested the following general procedure for relating mean x-ray absorption to fleshy fruit:

1. Develop a data set involving as large as possible spread in solids density values assuming that scanner resolution did not limit the measurements. One should minimize large fractures associated with shrinkage during drying by drying appropriately. Freeze drying is assumed herein, although drying over salt solutions could be used if steps were taken to minimize deterioration. Use the procedure as stated in variable interval (A).
2. Rewrite Equation 2 in expanded form:

$$\mu = (\rho_{WB}/\rho_t)\ (1\text{-}MCWB) * B + (\rho_{WB}*MCWB) * A + C \qquad [4$$

3. Rearrange Equation 4, treating the ice coefficient as a constant of 0.0182 mm^{-1}

$$\mu - 0.0182 * (\rho_W*MCWB) = [\ B * (\rho_{WB}/\ \rho_T)(1\text{-}MCWB)\ ][5$$

and regress the left hand side against the right hand side to estimate B without an intercept.

4. If the estimate of B is not significant ($P \leq 0.05$) then the density of solids contribution can be considered constant and developed into the intercept term. The intercept can then be estimated using univariate statistical approaches.

$$\mu - (\rho_{WB}*MCWB) * 0.0182 = C \qquad [6$$

Step 4 could be used immediately if it were assumed *a priori* that solids density contribution were constant. Fruit would not need to be frozen for this determination. The coefficient of 0.0182

mm^{-1} would be changed to 0.0191 mm^{-1} in instances where fruit tissue was not frozen.

Equations 4 - 6 show that gravimetric moisture and density effects are difficult to separate. However, with the apples comprising our data set, the solids ratio was observed to have little variation. When the coefficient associated with the solids ratio was found to be significantly different from zero, it was lower than the water term, as suggested by Equation 3. The low range in density, coupled with the lower influence of the solids term based on somewhat lower effective atomic number,suggests that the solids portion could probably be lumped into an intercept term. This leaves the moisture term, which is a product of wet basis moisture and wet bulk density. Using the appropriate coefficient for ice or water results in

$$\mu = D + B * MCWB * \rho_{WB} \qquad [6$$

where B is equal to 0.0191 mm^{-1} (water) or 0.0182 mm^{-1} (ice) and D is the intercept containing solids effects. X-ray absorption measurement could thus be used to estimate either wet basis moisture or wet bulk density, assuming one variable was known from other test procedures.

Because wet bulk density typically varies over a very narrow range with fleshy fruits, one could regard it as a constant in many instances. Equation 6 could be further modified to:

$$\mu = E + F * MCWB \qquad [7$$

where E and F are fitted constants. Thus, under conditions of constant density, x-ray absorption is a linear function of moisture content.

Physical Properties-Storage Study-Light Transmission

Combined results on the physical properties of apples obtained from Cornell University, Washington State University and USDA Appalachian Fruit Research Station are presented in Table 3. Apples studied ranged from un-affected apples to the most severely affected apples. Apples with severe watercore disorder (severity = 3 and 4) had a higher density than apples with a minor disorder or no disorder. This indicates that apples with severe watercore disorder can be separated from the others' base on the density differences.

At tissue level, moisture and density measured from un-affected and affected tissues for apples with different degree of watercore severity are presented in Table 4. Watercore severity had no effect on the moisture content within un-affected and affected apple tissue groups. However, affected tissue generally had higher moisture content (83.80%) than un-affected tissue (84.70%). Tissues obtained from severely (severity = 4) affected apples had significantly higher density than tissues from un-affected or minorly affected apples.

Effect of storage on the size and weight of apples with watercore disorder was evaluated. Size change was calculated as the difference between initial apple diameter and the diameter at the time of destructive evaluation. Weight change was calculated as the difference between weight before storage and at the time of destructive evaluation. There was no significant effect of storage condition on the size of apples (Table 5). However, apples stored under the refrigerated condition lost more weight (4.4%) than apples stored under the CA condition (1.8%). This

may be due to the high humidity in the plastic bags for CA storage which prevents dehydration during storage.

Under both refrigerated and CA storage conditions, moisture content from un-affected tissue of affected apples remained unchanged regardless of the severity of watercore (Table 6). However, moisture content of affected tissue from apples with severe watercore disorder was significantly higher than affected tissue from apples with mild watercore disorder (Table 6). Moisture difference between affected and un-affected tissues was also higher for severely affected apples than apples with mild disorder. Results reported here agree with the results presented in Table 3 and the literature (Marlow and Loescher, 1984) that affected tissue contains higher moisture content than un-affected tissue. However, total moisture content of affected apples may not be higher than apples without watercore disorder (Tables 3 and 5). Higher moisture of affected tissue than un-affected tissue may be simply because of the uneven distribution of moisture within the apple.

Effects of storage condition on moisture content of apple tissues and visual watercore severity scores are also presented in Table 5. Storage condition had no effect on the moisture content of un-affected tissue. Affected tissue from apples stored under the CA condition had a higher moisture content than that from apples stored under the refrigerated condition. Visual observation indicated that apples stored under the refrigerated condition had less severe watercore disorder (severity score = 1.69) than apples stored under the CA condition (severity score = 2.42). Myers (1983), Upchurch and Throop (1991) reported that

mild watercore disorder in apples will diminish during storage while apples with severe watercore disorder will experience internal breakdown. Does this mean that the watercore condition of affected apples stored under a refrigerated condition will lessen or develop the internal breakdown slower than in apples stored under the CA condition?

Visual evaluation of watercore severity on cut apples is a destructive method. In order to determine the extent of watercore disorder at the beginning of storage and how does the disorder changes with time, non-destructive evaluation is necessary. Non-destructive evaluation of watercore severity by light transmission is presented in Figure 6. There was no difference between light transmission scores of apples stored at the refrigerated and the CA conditions for the first two weeks. Subsequently, light transmission scores for apples stored at the refrigerated condition decreased faster than apples stored under the CA condition. Differences diminished after 20 weeks of storage when light transmission scores approached zero. This demonstrated that there was no difference between initial watercore severity of refrigerated (light transmission score = 0.433) and CA (light transmission score = 0.435) stored apples. However, differences developed during storage. Mean scores of visual watercore severity and light transmission at the time of destructive evaluation were 1.69 and 0.033, respectively, for refrigerated apples; comparable scores for CA-stored apples were 2.42 and 0.172, respectively (Table 4).

Upchurch and Throop (1991) indicated that a machine vision system to quantify light transmission can be used to classify core disorder in apples will diminish during storage [illegible] apples with severe watercore disorder will e[illegible] al breakdown. Does this mean that the watercore condition [illegible] ected apples stored under refrigerated conditions develop the internal breakdown slower than [illegible] the CA condition?

[illegible] al evaluation of watercore severity or [illegible] methods. In order to determine t[illegible] ex[illegible] [illegible] e disorder at the beginning of storage and [illegible] changes with time, non-destructive [illegible]

Non-destructive evaluation of [illegible] mission is presented in Figure [illegible]. There was [illegible] between light transmission ratio of apples [illegible] rated and the CA conditions for the first [illegible] ly, light transmission scores for apples st[illegible] condition decreased faster than apples stor[illegible] ondition. Differences diminished after [illegible] weeks [illegible] light transmission scores approached zero. [illegible] that there was no difference between initial [illegible] ore severity of refrigerated (light transmission [illegible] and CA (light transmission score = 0.435) stored apples [illegible] developed during storage. Mean [illegible] core severity and light transmission at the time of [illegible] were 2.59 and 0.073, respectively, for [illegible] ples) compared to [illegible] CA-stored apples [illegible] ively (Table [illegible]).

[illegible] (1991) suggested that a machine vision [illegible] can be used to classify apples into four degrees of watercore severity. They found system performance was dependent upon sensitivity of the camera. Changes in light transmission scores from the current storage study are presented in Table 7. For each watercore severity category, light transmission scores decreased with increasing storage time and is in agreement with the data presented in Figure 6. Apples with the highest watercore severity score (severity = 4) had the highest light transmission score regardless of storage time. Apples with an intermediate watercore disorder (severity = 2 or 3) had higher light transmission scores than apples with minor or no watercore disorder. However, the differences were not always significant for all storage time periods (Table 7).

CONCLUSIONS

X-ray CT can be used to nondestructively evaluate quality of fruit if internal characteristics can be associated with volumetric water content distribution. The following specific conclusions were drawn:

(1) Values for the water coefficient were found to approach $0.0191\ \text{mm}^{-1}$ and $0.0181\ \text{mm}^{-1}$, the accepted standard values for water and ice respectively.

(2) The values of the solids coefficient was usually not significantly different from zero, due in part to the narrow range associated with the solids density ratio variation in the physical measurement to the lower effective atomic number of the apple solids and to CT scanner resolution limits.

(3) X-ray CT can be useful for resolving differences in physiological structures within apples based on scanner measured volumetric water content differences since the relations are linear.

(4) A calibration procedure for fleshy fruits was developed, taking advantage of the constancy of the water coefficient at 0.0191 mm^{-1} (or ice at 0.0182 mm^{-1}). It is recommended that procedures outlined for the variable interval experiment (A) be used, making density measurements on pieces of fresh fruit as opposed to freeze-dried material. If steps were taken to minimize deterioration, drying over salt solutions would be preferable to freeze drying.

This study confirmed reports in the literature that apples with severe watercore disorder had a higher density than apples with mild or no watercore disorder. Moisture content of affected tissue from apples with severe watercore disorder was significantly higher than tissue from apples with mild disorder. Apples stored under refrigerated condition lost more weight (4.4%) than apples stored under CA condition (1.8%). Base on the light transmission scores, there was no difference between apples stored at either refrigerated or CA conditions initially. Subsequently, light transmission evaluation indicated that watercore disorder for apples stored under the refrigerated condition decreased faster than apples stored under the CA condition. Visual observation of cut apples confirmed that apples stored under refrigerated condition had less severe watercore disorder (severity score = 1.69) after storage than

apples stored under the CA condition (severity score = 2.42). This indicates that apples with watercore disorder may not be appropriated to store under a CA condition.

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[illegible] stored at [illegible] the CA condition (severity score [illegible] 2.0)

indicates that apples with watercore disorder may not be

stored under a CA condition.

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[illegible] work was supported by State and Hatch funds allocated to the [illegible] Agricultural Experiment Station and by a grant from [illegible]

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Table 1. Experimental Conditions and Data Ranges

Experiment	Volumetric Moisture (-)	Wet Bulk Density[1] (Mg/m^3)	Dry Bulk Density[1]	Tissue Density (Dry)[1] (Mg/m^3)	Drying Time (h)
1988 Watercore	0.65-0.85	0.9-1.1	0.11-0.14	Assumed = 1.0	-----
1989 Watercore	0.80-0.85	0.86-0.95	0.10-0.13	0.67-0.88	-----
1989 Repeated Interval	0.05-0.82	0.83-0.92	0.10-0.13	Assumed = 1.0	0-72
1989 Variable Interval (A)	0.05-0.82	0.8-0.95	0.10-0.16	0.8-1.1[1]	0-96
1989 Variable Interval (B)	0.0-0.85	0.82-0.91	0.11-0.13 [.18-1.33][2]	0.3-0.8	0-144

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[1] Bulk density and tissue density measured on samples of fresh fruit apart from the slices involved in drying

[2] Values obtained on individual fruit segments; probably not accurate due to difficulties in filling small fractures within the segment with the glass beds in the Chinnan et al. (1988) procedure

Table 2. Summary of Modeling Results

Experiment[1]	Density	Moisture	Case[2]	Equation[3]	Error DF	R^2	Mean Square Error
1988 Watercore	ns	Linear	1	$\mu = 0.0005 + 0.022 * \theta$	34	.79	0.0020
			2	$\mu = 0.024 * \theta$	34	---	------
1989 Watercore	ns	ns	-	------	38	---	------
1989 Repeated Interval	ns	Linear & Quadratic	3	$\mu = 0.0005 + 0.0306 * \theta - 0.0174 * \theta^2$	14	.97	0.0001
1989 Variable Interval (A)	ns	Linear	1	$\mu = 0.0023 + 0.0190 * \theta$	15	0.97	0.0001
	ns	Linear	1B	$\mu = 0.0014 + 0.017 * \theta$	15	0.94	0.0001
	*	Linear	2B	$\mu = 0.0015 * \frac{\rho_{wb}}{\rho_t} + 0.0182 * \theta$	15	---	------
1989 Variable Interval (B)	ns	Linear	1	$\mu = 0.019 + 0.0142 * \theta$	21	.86	0.0017
			2	$\mu = 0.0176 * \theta$	21	---	------

[1] Results not shown for the 1989 watercore experiment due to the limited range of available moisture and density of apples in this test

[2] Case 1 = regression with computed intercept
1B = same as Case 1, except that fruit were frozen
2 = regression with intercept forced to zero
2B = regression with intercept forced to zero and the moisture term set to 0.0182 mm^{-1}, the value for ice. Fruit was frozen.
3 = regression with 2nd order moisture term

[3] μ = x-ray absorption (mm^{-1})
θ = volumetric water fraction $\frac{mm^3 \text{ water}}{mm^3 \text{ bulk fruit}}$
ρ_b = dry bulk density (Mg/m^{-3})
ρ_t = dry tissue density (Mg/m^{-3})
A,B = coefficients (mm^{-1})
C = intercept (mm^{-1})

Table 3. Physical properties of apples with different degree of watercore disorder.

Watercore Severity[*]	Density (g/cm^3)	Apple Tissue Moisture (%) Un-affected	Apple Tissue Moisture (%) Affected	Apple Tissue Density (g/cm^3) Un-affected	Apple Tissue Density (g/cm^3) Affected
0	0.852^b	84.70		0.702^b	
1	0.853^b	83.51	84.56	0.685^b	0.714^b
2	0.862^b	84.01	84.80	0.681^b	0.714^b
3	0.907^a	84.12	84.86	0.709^b	0.712^b
4	0.940^a	84.62	85.04	0.938^a	0.978^a

* Scale of 0=no disorder to 4=severe disorder.

[a-b] Values in the same column which are not followed by the same letter are significantly different ($P<0.05$).

Table 4. Effect of storage condition and watercore severity on moisture content of apple.

		Moisture Content (%)		
Storage Type	Watercore Severity*	Un-affected Tissue	Affected Tissue	Difference
Refrigerated	0	84.15		
	1	83.14	83.42[b]	0.29
	2	83.63	84.17[a]	0.54
	3	83.35	84.14[a]	0.79
	4	83.58	84.04[a]	0.47
CA	0	84.30		
	1	82.71	82.98[c]	0.27
	2	82.75	83.71[b]	0.96
	3	83.65	84.66[a]	1.01
	4	83.76	84.79[a]	1.04

* Scale of 0=no disorder to 4=severe disorder.

a-c Values in the same column which are not followed by the same letter are significantly different ($P<0.05$).

Table 5. Effect of storage condition on size and weight changes of apples.

Storage Type	Size Change* (mm)	Weight Change** (g)
Refrigerated	1.05[a]	6.52[a]
CA	0.73[a]	2.66[b]

* Mean Diameter = 69 mm

** Mean Weight = 147 g

a-b Values in the same column which are not followed by the same letter are significantly different ($P<0.05$).

Table 6. Effect of storage condition on watercore severity and moisture content of apple.

		Moisture Content (%)		
Storage Type	Watercore Severity*	Un-affected Tissue	Affected Tissue	Difference
Refrigerated	1.69[b]	83.63	84.03[b]	0.53[b]
CA	2.42[a]	83.65	84.47[a]	0.99[a]

* Scale of 0=no disorder to 4=severe disorder.

a-b Values in the same column which are not followed by the same letter are significantly different (P<0.05).

Table 7. Effect of watercore severity and storage time on the light transmission scores of watercore affected apples.

Watercore Severity*	Light Transmission Score Storage Time (weeks) 0	2	4	6	8	12	16	20	24	At Destruction
0	0.219^{bc}	0.220^{bc}	0.152^{bc}	0.088^{bc}	0.026^{bc}	0.003^{b}	0.000^{b}	0.003	0.001	0.001^{b}
1	0.062^{c}	0.057^{c}	0.045^{c}	0.005^{c}	0.000^{c}	0.003^{b}	0.000^{b}	0.003	0.000	0.003^{b}
2	0.359^{b}	0.278^{bc}	0.176^{bc}	0.105^{bc}	0.061^{bc}	0.035^{b}	0.000^{b}	0.002	0.000	0.131^{ab}
3	0.422^{b}	0.390^{b}	0.349^{b}	0.316^{b}	0.222_{b}	0.079^{b}	0.058^{ab}	0.037	0.003	0.140^{ab}
4	0.848^{a}	0.800^{a}	0.751^{a}	0.648^{a}	0.477^{a}	0.306^{a}	0.198^{a}	0.115	0.026	0.211^{a}

* Scale of 0=no disorder to 4=severe disorder.

a-c Values in the same column which are not followed by the same letter are significantly different ($P<0.05$).

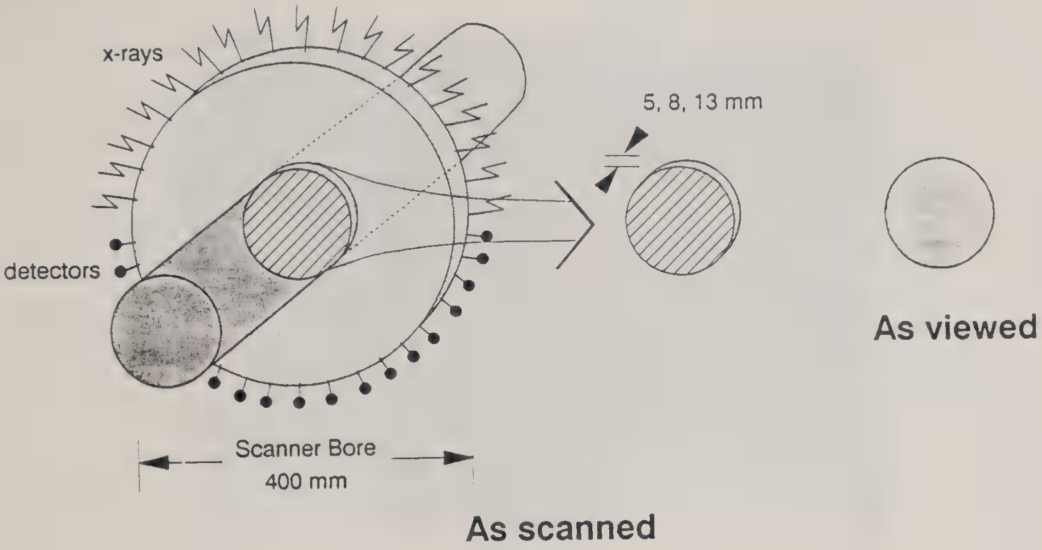

Figure 1. Schematic diagram showing an arbitrary object in a CT scanner, highlighting the scanned plane and the "as viewed" cross section seen on the display.

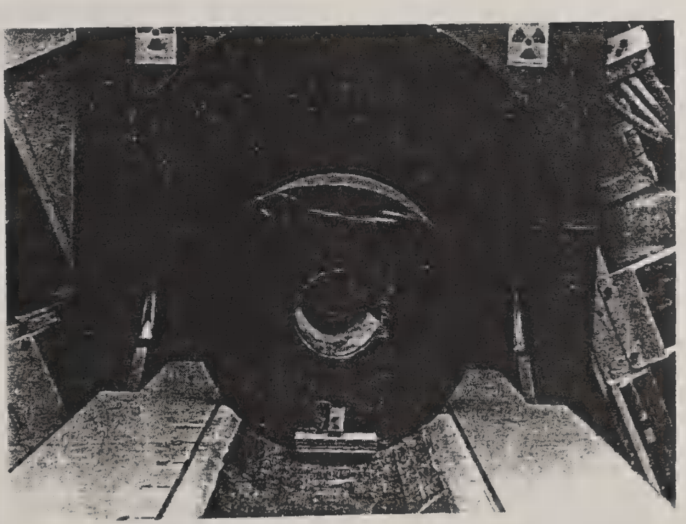

Figure 2. Photograph of whole-fruit jig for scanning fresh apples.

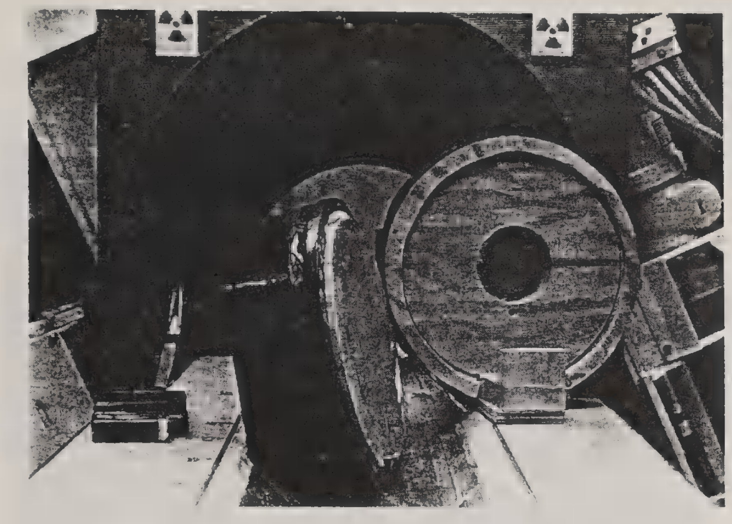

Figure 3. Fruit-slice jig for scanning individual slices.

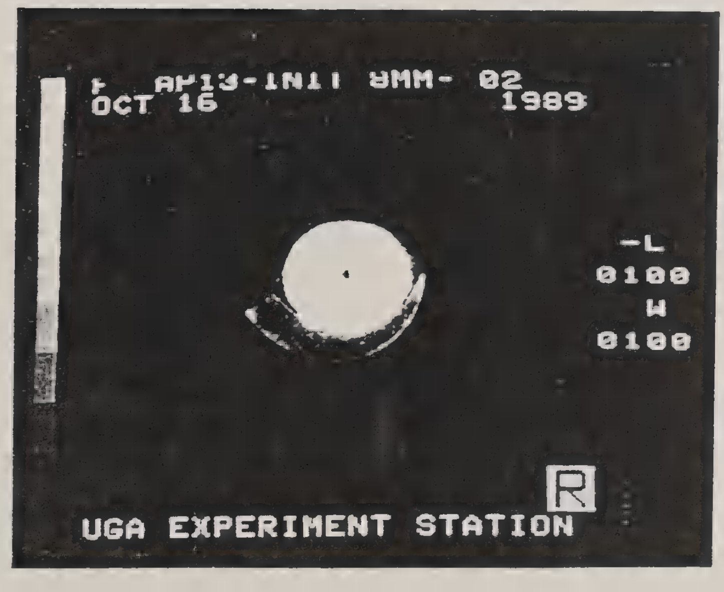

Figure 4. CT image of a fresh apple.

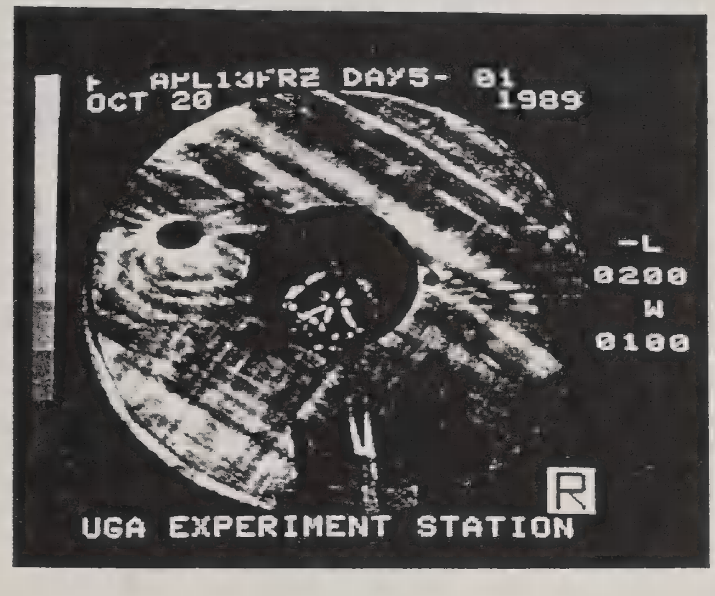

Figure 5. CT image of an apple slice after 96 h in a freeze-drier.

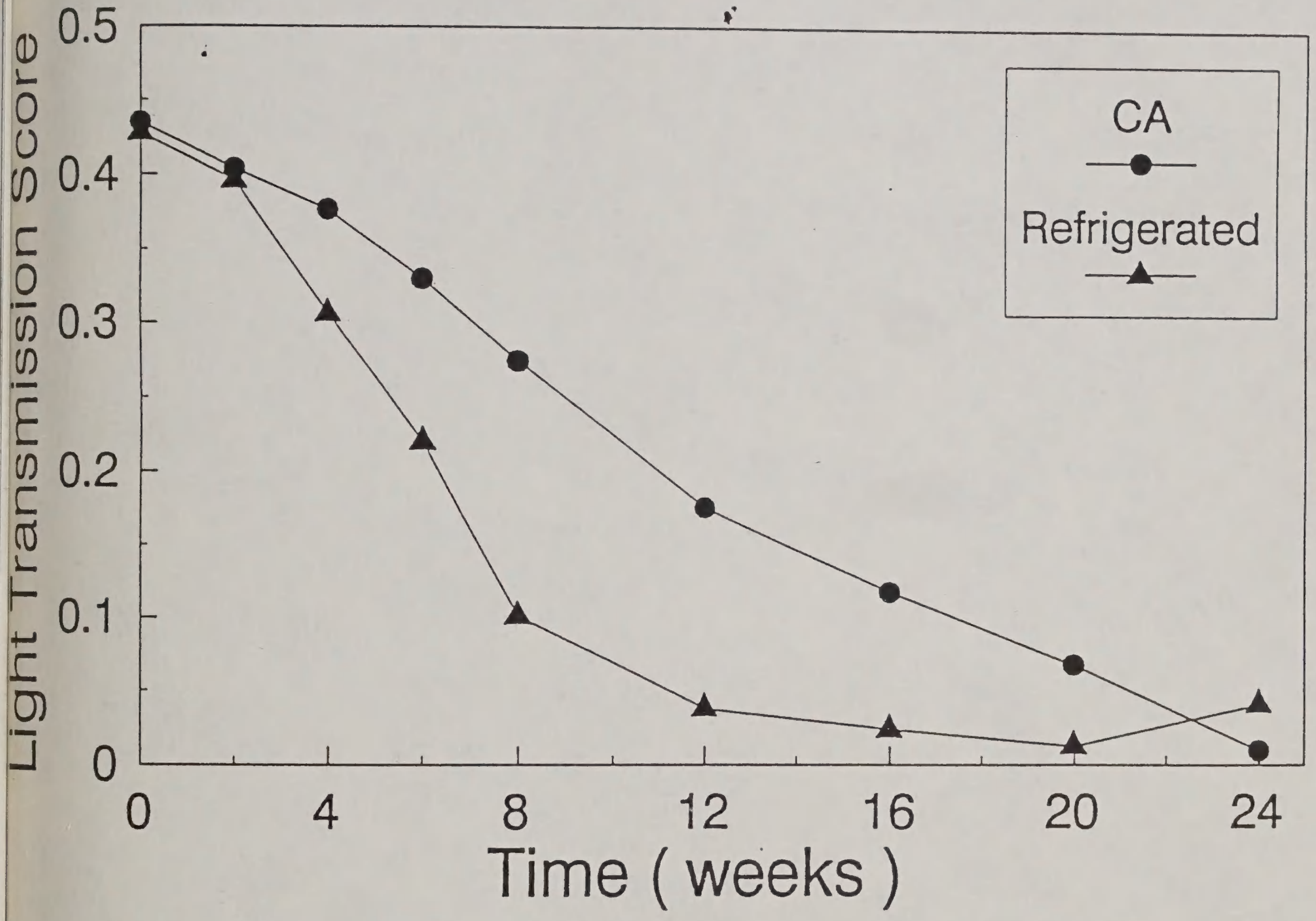

Figure 6. Effect of storage time on the light transmission scores of apples.