PHYSICAL RESPONSES OF FLUE-CURED TOBACCO STORED IN THE FORM OF BALES[1,2]

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Tobacco was stored in small bales of volume 0.05m^3 with dimensions 30 x 30 x 60 cm in 1996 and 38 x 38 x 38 cm in 1997 and 1998. Treatments were arranged in a factorial of three densities 259, 324 and 388 kg m^{-3} and three moisture contents 12, 16 and 20% (wet basis). The area (outside bale), volume (inside bale), and intensity of decay were estimated after seven weeks of storage in 1996 and thirteen weeks of storage in 1997 and 1998. Both volume and intensity of decay on the inside of the bales was positively correlated (P<0.01) with the moisture content of the baled tobacco. There was no significant correlation (P<0.05) between either volume or intensity of decay on the inside of the bale with density of the baled tobacco. Around the outside, decay was most likely to develop where air circulation around the outside surface had been prevented. Inside the bales, decay was most likely to be found in the proximity of decay on the outside. Decay was observed to originate from centers of decay initiated by factors such as leaves being insufficiently cured or by the presence of damp foreign matter. Centers of decay were found at all established moisture contents and bale densities. A natural migration of moisture from the interior to the exterior of the bales was observed, but migration was hindered by the presence of folded leaves. Folded leaves could thus serve as centers of decay.

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INTRODUCTION

Flue-cured tobacco in Georgia has, for at least 25 years, been transported between the farm and the factory as loose leaf, in burlap sheets, with a maximum weight of 125 kg (15). Though this has been the normal routine, there are reasons for considering other forms of material handling. As early as 1967 a mechanized system of receiving flue-cured tobacco at the warehouse was evaluated (3). This system used burlap sheets with a conveyor for unloading those sheets of tobacco from the farmer's vehicle and carrying them to the weigh scales. The sheets of tobacco were moved on long pallets by fork lift trucks to other parts of the warehouse. The tobacco then was transported to the manufacturer in the same sheets, stacked high on a flatbed tractor trailer.

Compressed plant material, such as tobacco leaf, has a tendency to relax through time. The amount of relaxation is related to age and moisture content (1). This phenomenon may affect the shape of a package over time and limit the extent to which packages may be stacked. In order to increase the amount of tobacco that could be stacked on a vehicle, it was thought advantageous to provide some physical support to the untied tobacco during haulage. Sowell et al. (14) suggested a collapsible pallet box that could be filled with tobacco. Such boxes would be filled by the farmer and brought to the warehouse, where they would be handled entirely by forklift trucks. The density of tobacco in the boxes was reported as similar to that of tobacco in sheets, even as high as 194 kg m^{-3}. Packing the tobacco was achieved by walking on the tobacco while the boxes were being filled. Otherwise, the tobacco was unrestrained. Sale of the tobacco would take place with tobacco still in the pallet box. The rigidity of the pallet boxes enabled them to be stacked on a flatbed tractor trailer for subsequent transport to the tobacco manufacturer. By being collapsible, only a minimal expense was incurred to return the pallets for reuse from the tobacco manufacturer to the farmer.

In order to further increase the amount of tobacco that could be carried within the legal capacity of a vehicle, tobacco would need to be supported at a higher density than obtained by simply pressing down the tobacco inside a sheet or box. By baling tobacco leaf and supporting the integrity of those bales with disposable binding material, nothing would need to be returned for reuse. Tobacco has been packaged in bales within the burley tobacco market for many years (16). Tobacco has been sorted by grade on the farm and then packaged into a bale according to grade. Bales of similar grade have then been stacked on a flat pallet and moved by forklift on the warehouse floor. In 1968, Watkins (17) experimented with flue-cured tobacco in North Carolina using a horizontal bale press of dimensions 30 x 76 x 38 cm. Bale densities varied from 205 to 307 kg m^{-3}. In 1968 Humphries (8) reported that in Metter, Georgia, bales weighing 362 to 407 kg and of dimensions 76 x 102 x 122 cm were being made and sold in a warehouse in a project sponsored by several tobacco companies. More recently, there has been a renewed interest in the reduction of material handling expenses between farm and factory. In 1996, bales of approximate dimensions 112 x 112 x 122 cm were made in both North Carolina and Georgia to once again search for suitable baling criteria (13).

Tobacco leaf, being a biological material, is likely to spoil whenever conditions exist that encourage the onset of mold and decomposition. When tobacco is being packaged and stored in that package, it is likely that there are conditions for the tobacco that must be met in order for the tobacco not to spoil. The authors have identified some of the factors known to influence the degree of spoilage in stored tobacco as being: maturity and cure of the tobacco; moisture content of the tobacco (11); density of tobacco in the package; and the temperature, relative humidity and movement of the air within the storage environment around

[1] Supported by Hatch, State and USDA funds allocated to the University of Georgia College of Agriculture Experiment Stations as well as funds from the Georgia Agricultural Commodity Commission for Tobacco.

[2] The use of trade names in this publication does not imply an endorsement by the authors of the product named, nor criticism of ones not mentioned.

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the package. In order to minimize spoilage, it is necessary to know the range of values permissible within each of these factors.

Watkins (17) observed that, for small bales of tobacco of different densities and moisture contents, lower stalk tobacco was safely stored for 30 d in bales having a density as high as 205 kg m^{-3} and a moisture content (wet basis) as high as 21%. Upper stalk tobacco was safely kept for 30 d in bales having a density of 307 kg m^{-3} and a moisture content of 17.2%. The tobacco was grown, baled and stored in North Carolina. Walton et al. (16) reported that bales containing tobacco harvested and stored in Kentucky at a high moisture level were often graded as unsound because of the undesirable odor caused by bacterial activity.

If both the moisture content and density of tobacco within a package need to be controlled within a range of acceptable values, then those values must be easily determined for the tobacco in question. If tobacco is being baled, then the density of the tobacco in the bales is controlled by the weight of tobacco being pressed into a known confined space; uniform density is influenced by the uniform distribution of tobacco in the bale chamber prior to compression. Moisture content is, however, more difficult to determine and control.

The measurement of tobacco moisture content has been investigated in multiple studies (6,7,10). Since tobacco is sold by weight, as well as by grade, it is in the farmer's interest to put back into the leaf, following curing, the maximum amount of moisture without encouraging decay. With insufficient moisture, the leaf would shatter when handled, but too much moisture encourages the onset of mold and decomposition of the leaf. The varying characteristics of tobacco including temperature and the way it is presented to a moisture measuring technique influence the moisture reading obtained.

A change in temperature of biological material may indicate decomposition (12) and a linear relationship has been established between temperature rise and dry matter loss. The relationship between the onset of mold or decay and temperature rise has not been reported for tobacco. However, the monitoring of temperature in baled tobacco may be a way of detecting if and when such biological decomposition occurs.

Flue-cured tobacco grown in Georgia is known to have the propensity for higher sugar content than tobacco grown in some other areas, and is likely to be stored under a higher temperature and humidity than tobacco stored in some other states (Personal communication, M. Boyette, N.C. State University). Furthermore, storage may be for the short term as well as the long term. For example, holding tobacco from the first harvest to the end of the sales season could amount to 13 weeks or more, whereas storage from one season to the next could amount to 12 months or more. In either case, storage may take place in an uncontrolled environment. Since there are so many variables associated with the safe storage of tobacco in bale form, an experiment was conducted to investigate those variables as related to cured flue-cured tobacco grown in Georgia when baled at different densities and moisture contents.

MATERIALS AND METHODS

1996 Season

Tobacco, variety 'K 326', was harvested from the upper part of the stalk (harvest 3) during the first and second weeks of August. Tobacco for the described experiment was stored in a packhouse from harvest until December. Bale weight and density calculations were based upon the condition of the tobacco after storage in the packhouse.

A simple baler was built which would help form bales of size 30 x 30 x 60 cm at required densities. The design was based upon that used for baling pine straw (2). It was of wooden construction, with a long metal handle for manually applying pressure to the contents of the bale chamber.

After storage in the packhouse, moisture content of the tobacco was determined by the oven dry method. Two representative samples were weighed and placed in large drying ovens. The samples of tobacco were dried by holding the temperature inside the ovens at 37°C for 96 h, a temperature considered unlikely to cause chemical breakdown within the leaf. The samples were then removed and weighed once again, and the difference in weight was considered to be the moisture removed during drying of the tobacco. The moisture content of the entire tobacco was calculated on a wet weight basis by dividing the weight of water removed by the weight of the original sample.

The experimental treatments were designed as a 3 x 3 factorial of three densities (259, 324 and 388 kg m^{-3}) and three moisture contents (12%, 16% and 20%). Based on the pre-determined original moisture content of the tobacco, calculations were then made as to the weight of water necessary to raise the prescribed amount of tobacco to the required moisture contents for tobacco at each of the three densities. There was sufficient tobacco for almost two replications of the treatment variations. Any shortage of bales for the second replication was limited to those bales of the least moisture content.

During adjustment of tobacco to the appropriate moisture content for each treatment, the prescribed weight of tobacco for a treatment was placed in a chicken wire mesh basket on a platform balance. Then the required weight of water was sprayed over the tobacco in a superfine mist of approximately 100 microns at 1.9 L/min (Foggit-waterlog, Foggit nozzle Co, San Francisco, CA). Water was added while the tobacco was manually mixed in order to ensure an even distribution of water over the leaf and until the tobacco plus water came to the required weight for the tobacco at the prescribed moisture content of a given treatment. Absorption of moisture into the tobacco leaf was encouraged through raising the temperature of the leaf to

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Figure 1. Baler used during the study, 1997 and 1998.

37°C by placing the wire mesh baskets of tobacco inside a tobacco barn and heating the barn to the required temperature. A procedure of wetting and heating was repeated until the tobacco was confirmed to be of the correct weight with no apparent surface moisture. This procedure sometimes took several days to complete.

Tobacco of each treatment and replication was then baled to a final dimension of 30 x 30 x 60 cm. Each bale was held together with two strands of #12 gage baling wire, placed lengthwise over the bale, in order to support the shape of the bale. Finally, as a suggested means of maintaining the original moisture content of the tobacco in the bales during storage, each bale was placed inside three concentric polyethylene bags.

For storage, the bales were placed in another small tobacco barn, of equivalent capacity to only 30 racks of tobacco. The bales were placed on their ends, in two rows side by side with one replication in each row. They were placed along the center of the barn in order to have them away from the sides of the barn and to provide a convenient passageway through the barn to any of the bales.

The climate of the storage barn was then established at a temperature of 27°C and 77% relative humidity; these values represent the average temperature and humidity for the local tobacco producing district during the month of July (4). Since the bales of tobacco were coated with an impervious wrapping material, maintenance of humidity was considered to be less critical than maintenance of temperature. The temperature was maintained by three 1300 W electrical fan space heaters during outside temperatures at or above 10°C and assisted by heat from the tobacco barn furnace when outside temperatures were below 10°C.

As a suggested means of detecting biological activity and thus decomposition within the bales (12), the temperature of each bale was monitored. Two type K thermocouples were installed inside each bale 15 cm from one end with each being 15 cm from either side of the bale. These thermocouples were connected to a Campbell 21X data logger (Campbell Scientific Inc., Logan, Utah). The air temperature was monitored both inside and outside the storage barn.

Three bales were examined after 31 d of storage, rewrapped and returned to their respective sites in the barn. After being stored for 49 d (seven weeks) all bales were examined. Any change in moisture content of the bale was detected by weighing each bale while deducting the weight of the wire and wrapping material. A visual examination was then undertaken with each bale being assessed for surface mold and decay. Internal mold or decay was assessed once the bale had been broken open.

The areas of mold or decay on the outside of each bale and the volume of mold or decay on the inside of each bale were estimated as a percentage (%) of the total surface area or volume of the bale. The intensity of mold or decay was rated on a scale of 1 (least) to 10 (most) as follows: 0 - no mold; 1 - fine mold on surface of tobacco that fluffs off when touched; 2 - more extensive surface mold; 3 - tobacco discolored to a darker color as a result of mold, may still sell; 4 - faint smell, powdery, breathing of the dust is unpleasant; 5 - noticeable smell, tobacco may be warm, yet not be visibly wet, sometimes yellow mold; 6 - some decay, tobacco definitely not suitable for resale; 7 - decay, leaf will easily pull apart; 8 - breakdown of tobacco leaf structure; 9 - more extensive breakdown of tobacco leaf structure; 10 - rotten leaf. Henceforth in the text, all forms of mold or leaf breakdown are collectively referred to as decay.

1997 Season

Tobacco, variety K 326, was harvested from the lower (harvest 1), middle (harvest 2) and upper (harvest 3) leaf positions on July 5, July 23 and August 19, respectively. Once cured, tobacco from each of the three harvests was left in the curing barn without being brought into order, until the moisture content of the tobacco was determined by the oven dry method on a wet basis. The same factorial design used in 1996 was established with three densities (259, 324 and 388 kg m^{-3}) and three moisture contents (12, 16 and 20%). There was sufficient tobacco available for almost two replications at each harvest.

As in 1996, tobacco was manipulated to establish the required moisture content for the treatments. The bale

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chamber volume was maintained at 0.05 m^3, but modified from that of 1996 to a cubic bale shape of 38 x 38 x 38 cm (Figure 1). This modified shape was chosen because it: was a miniature version of large bales being made on farms; had internal cross sectional area more likely to allow a tobacco leaf to lie unfolded in the bale; resulted in a greater distance from the outside to the center of the bale; remained a manageable size for research purposes. The bales for each of the three harvests were placed in storage on July 18, August 18 and September 5, respectively.

The bales were stored in three separate storage rooms according to their moisture content, 12%, 16% or 20%. Within each room, the bales were placed upon plywood shelves but the bales were not enclosed in plastic wrapping material as in 1996. A single thermocouple wire was inserted into the center of each bale to monitor temperature variations. No climate control was provided except to keep the rooms closed during the storage period.

The bales of tobacco from each harvest were stored for approximately 13 weeks and then examined on October 20, November 19, and December 9 for the three harvests. The bales were weighed to determine the moisture content and core samples were taken to determine the moisture content using a freeze-dry procedure (Bill Ward of Export Leaf Tobacco Company, 2400 Old Stantonsburg Road, Wilson, NC 27893). The tobacco was inspected for internal and external decay as in 1996.

As a means of examining the uniformity of compaction of the bales, one bale at 12% moisture and 324 kg m^{-3} was prepared for passing through an EMI 5005 X-Ray CT Scanner (EMI Ltd, Middlesex, UK). While being firmly supported using extra wire, the bale was sawn into four equal sections, each perpendicular to the layers of tobacco leaf in the bale and each section being small enough to pass through the scanner.

1998 Season

Tobacco, variety K 326, was harvested from the lower (harvest 1), middle (harvest 2) and upper (harvest 3) leaf positions on June 18, July 7, and August 4, respectively. It was prepared for storage as in 1997.

Bales for each of the three harvests were placed in storage on July 23, August 28 and September 14, respectively, in three separate rooms according to their moisture content, 12%, 16%, or 20% as in 1997. In contrast with previous years, all bales were placed on slats in order to enhance air circulation around the bales. In addition, bales were not enclosed in plastic wrapping material as in 1996. Thermocouples were again inserted into the center of the bales to monitor temperature variations during the storage period. No climate control was provided except to keep the rooms closed during the storage period. At the time bales from the second and third harvest were added to the storage rooms, bales from the previous harvest(s) were weighed. By this procedure the rate of drying could be observed.

The bales of tobacco from each harvest were visually inspected for any form of decay after approximately 13 weeks in storage, the first harvest on October 28, the second harvest on November 27, and the third harvest on December 14. At the time of examination, moisture content was determined by weight and by the freeze dry procedure as in previous years.

As with the nondestructive testing of 1997, three bales were passed through a Toshiba CAT scanner, model TCT-20A, with a high density beam. The bales scanned were from the second harvest at 12% moisture and 259 kg m^{-3}, the third harvest at 20% moisture and 259 kg m^{-3}, and the third harvest at 20% moisture and 388 kg m^{-3}. Bales were inspected for the presence of excess moisture or density variations, decay or centers of decay; and for foreign material such as swollen or undried stems. In order to investigate development of decay during long term storage, the three bales from 1998 that were passed through the CAT scanner were held over until March 17, 1999 before being opened, a period of approximately 29 weeks for the bale from the second harvest and 26 weeks for the two bales from the third harvest.

The tobacco was examined after 7 weeks in 1996, after 13 weeks in 1997 and after 13 weeks in 1998 with three bales being examined after 26 weeks in 1998. If decay was to be found under such short periods then it would likely be found after longer periods of storage, especially as the tobacco was stored in uncontrolled environments.

Table 1. Correlations between area or volume of decay and intensity of decay with moisture content and density of baled tobacco from first harvest, 13 weeks after storage in 1997 and 1998.

	Outside the Bale		Inside the Bale	
	Area of Decay	Intensity of Decay	Volume of Decay	Intensity of Decay
Moisture	-0.3404	0.3037	0.7743 **	0.6690 **
Density	0.2113	- 0.0849	0.0072	0.0900

* Denotes significance at the P<0.05 level with n = 26, where n = experimental unit = bales.
** Denotes significance at the P<0.01 level with n = 26.

Table 2. Correlations between volume and intensity of decay inside bales with area and intensity of decay outside baled tobacco from first harvest, after 13 weeks of storage in 1997 and 1998.

		Outside the Bale	
		Area of Decay	Intensity of Decay
Inside the Bale	Volume	-0.3958 *	0.2678
	Intensity	-0.3967 *	0.3345

* Denotes significance at the P<0.05 level with n = 26, where n = experimental unit = bales.
** Denotes significance at the P<0.01 level with n = 26.

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Because of the variation in the number of bales of cured tobacco available used each year and for each harvest, we used correlation analyses rather than analysis of variance to determine the relationship of data variables with each other (PC SAS, SAS Inst. Inc., Cary, NC). When the amount of tobacco was sufficient to have a replicated design, this was done within a year. Correlation analyses by year revealed that years had no significant ($P<0.05$) effect on the relationships among variables, and thus could be used as replications of treatments. However, the effect of year was removed before correlation analyses were conducted.

RESULTS AND DISCUSSION

Moisture content and density versus area or volume and intensity of decay

The three individual harvests are considered for each of the three years. In harvest 1, which consisted of the lower leaves during 1997 and 1998, both volume and intensity of decay on the inside of the bales were positively correlated ($P<0.01$) with the moisture content but not with density of the tobacco inside the bales (Table 1). On the other hand, area and intensity of decay on the outside of the bales were not significantly correlated with either moisture content or density. It was also noted that the volume and intensity of decay on the inside of the bales were negatively correlated ($P<0.05$) with the area of decay on the outside of the bales (Table 2).

For harvest 2, comprised of middle leaves, during years 1997 and 1998, both volume and intensity of decay on the inside of the bales were positively correlated ($P<0.01$ and $P<0.05$ respectively) with the moisture content of the tobacco in the bales but not with density (Table 3). On the other hand, area and intensity of decay on the outside of the bales were not significantly correlated with moisture content. Neither the volume nor intensity of decay on the inside of the bales were correlated ($P<0.05$) with area and intensity of decay on the outside of the bales (Table 4).

For leaves from harvest 3 in all three years, 1996 to 1998, both the volume and intensity of decay on the inside of the bales were positively correlated ($P<0.01$) with the moisture content of the tobacco in the bales but not with bale density (Table 5). In contrast with other harvests, intensity of decay on the outside of the bales was significantly correlated ($P<0.05$) with moisture content. It was also noted that the volume and intensity of decay on the inside of the bales was correlated ($P<0.01$) with area of decay on the outside of the bales; volume of decay on the inside was correlated ($P<0.01$) with area of decay on the outside of the bale (Table 6). There also was a positive correlation ($P<0.05$) between intensity of decay on the inside and intensity of decay on the outside of bales.

When averaged over all harvests for all years, both the volume and intensity of decay on the inside of the bales were positively correlated ($P<0.01$) with the moisture content of the tobacco in the bales but not with bale density (Table 7). The intensity of decay on the outside of the bales was positively correlated ($P<0.01$) with the moisture content of the tobacco. Similarly, both volume and intensity of decay on the inside of bales were positively correlated ($P<0.01$ and $P<0.05$, respectively) with the intensity but not area of decay on the outside of the bales (Table 8).

Finally, for both inside and outside the bale, the intensity of decay was positively related to the quantity of decay (Table 9). The second and third harvests had the most significant correlations ($P<0.01$) for outside of the bales; the first and third harvests had the most significant correlations ($P<0.01$) for inside of the bales.

Observations of stored leaf

After only seven weeks of storage in 1996, at least some decay was observed on the outside of most of the bales. However, the degree of mold varied from bale to bale. The occurrence of fine mold on the outside of bales was enhanced by the polyethylene wrapping material used to maintain the internal moisture content of the bale at the original level. Condensation occurred on the inside of the wrapping material in close proximity to the tobacco. It is suggested from this observation that bales of tobacco need to be free standing to allow air circulation around them. There was a noticeable difference between the amounts of decay associated with the stored bales of 1997 compared

Table 3. Correlations between area or volume of decay and intensity of decay with moisture content and density of baled tobacco from second harvest, after 13 weeks of storage in 1997 and 1998.

	Outside the Bale		Inside the Bale	
	Area of Decay	Intensity of Decay	Volume of Decay	Intensity of Decay
Moisture	0.2122	0.3133	0.5441 **	0.4412 *
Density	- 0.0182	0.0425	0.1284	0.2499

* Denotes significance at the $P<0.05$ level with n = 26, where n = experimental unit = bales.
** Denotes significance at the $P<0.01$ level with n = 26.

Table 4. Correlations between volume and intensity of decay inside baled tobacco with area and intensity of decay outside baled tobacco from second harvest, after 13 weeks of storage in 1997 and 1998.

		Outside the Bale	
		Area of Decay	Intensity of Decay
Inside the Bale	Volume	0.1818	0.1221
	Intensity	0.1029	0.2130

* Denotes significance at the $P<0.05$ level with n = 26, where n = experimental unit = bales.
** Denotes significance at the $P<0.01$ level with n = 26.

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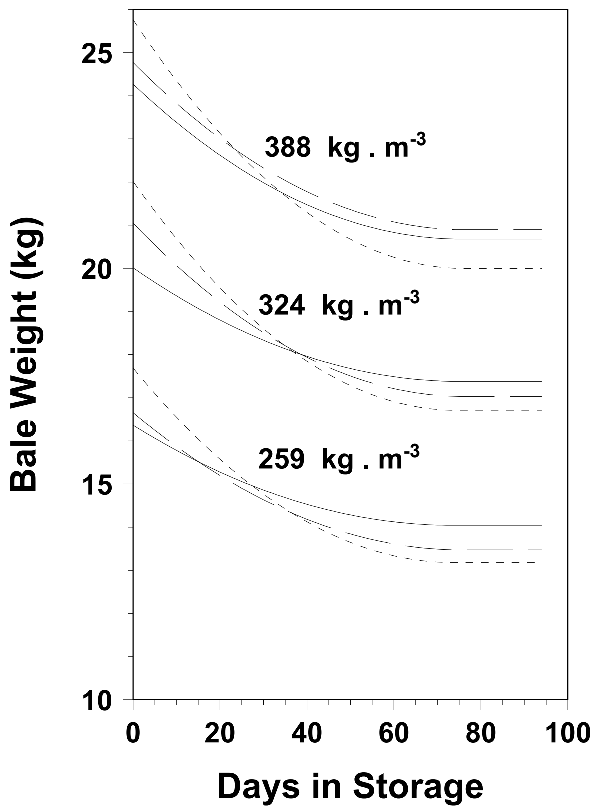
Figure 2. A Variation in the weight of bales of tobacco during storage according to moisture content 12% ———, 16% — —, 20% - - - - , for each density of harvest 3, 1998.



with those of 1996. Having the bales unwrapped in 1997 allowed air circulation to take place around the bales except for the base. In 1997 the bales were placed on solid plywood. Decay on the outside of the bales was often found on the base of the bales adjacent to the solid surface on which they were sitting. The appearance of decay on the outside of the bales was further reduced in 1998 compared with 1997 by placing the bales on slats rather than on a solid plywood base, thus allowing more air to circulate around some of the base.

Internal decay was found either in the vicinity of the base or on top of the bales, often in conjunction with decay on the outside of the bale, or in the vicinity of insufficiently cured leaf or damp foreign material within the bales. For all bales having internal decay, decay was more likely to be found originating from centers of decay rather than uniformly throughout the bales.

During 1997, these centers of decay originated from insufficiently cured leaves. Care was taken to distinguish between decay and black leaf that had resulted from damage to the leaf at harvest time. White speckles on the leaves were attributed to pre-storage conditions. Yellow mold was evident on tobacco within most bales.

In 1997, the general level of decay intensity inside the bales was higher for the second harvest than for the other two harvests. In fact, some decay was found inside all bales from that harvest. It is suggested that the larger leaves of the middle stalk tobacco, being longer than the width (38 cm) of the bale chamber, were likely folded in the bales, thus preventing the complete migration of moisture to the outside of the bales and resulting in accumulation of moisture and a center of decay. Tobacco exposed to the outside of the bales was dry and crisp. This would imply that tobacco in the bales should be uniformly layered in the bales to encourage the movement of moisture from the interior to the exterior of the bales during storage. The use of small bales may be considered a worst-case scenario since larger bales of the size being considered for commercial use (for example 102 x 102 x 107 cm) would be wider than the length of a leaf, and a lower probability of leaf folding to occur. In order to encourage a flat open configuration of leaves within the bale chamber, a leaf spreader would be helpful as part of the baler design.

In 1998, internal decay was observed towards the base of the bales even when the bales were placed on slats. It was thought, though not verified, that repeated movements of the compression ram inside the bale chamber led to tobacco of a higher density near the base of the bales. As a result of the study it would seem more desirable to have a single compression stroke of the ram inside the bale chamber with all tobacco for a bale being compressed with one stroke rather than compressing the tobacco as it is loaded into the compression chamber.

In 1998, the second-harvest tobacco had a brighter color than tobacco of the other two harvests. Tobacco of the third harvest was noticeably darker than that of the second harvest and there was considerably more decay in the tobacco baled from the third harvest than from the second. The tobacco may have been harvested before it was fully ripe since some of the cured leaves were noted to be slightly green. As a result of this study, it is suggested that the

Table 5. Correlations between area or volume and intensity of decay with moisture content and density of baled tobacco from the third harvest, after 7 weeks of storage in 1996 and after 13 weeks of storage in 1997 and 1998.

	Outside the Bale		Inside the Bale	
	Area of Decay	Intensity of Decay	Volume of Decay	Intensity of Decay
Moisture	0.2149	0.3162 *	0.4862 **	0.6394 **
Density	0.0854	- 0.0311	0.1926	0.2515

* Denotes significance at the P<0.05 level with n = 39, where n = experimental unit = bales.
** Denotes significance at the P<0.01 level with n = 39.

Table 6. Correlations between volume and intensity of decay inside baled tobacco with area and intensity of decay outside baled tobacco from the third harvest, after 13 weeks of storage in 1997 and 1998.

		Outside the Bale	
		Area of Decay	Intensity of Decay
Inside the Bale	Volume	0.4630 **	0.4711 **
	Intensity	0.4446 **	0.3373 *

* Denotes significance at the P<0.05 level with n = 39, where n = experimental unit = bales.
** Denotes significance at the P<0.01 level with n = 39.

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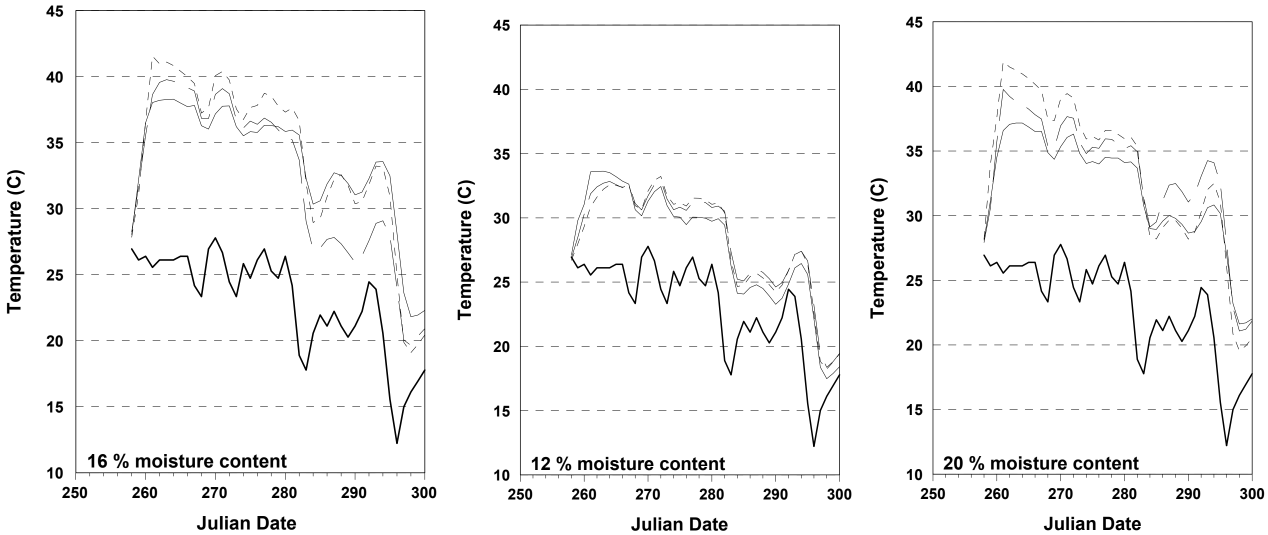
Figure 3. Variation in the temperature of bales of tobacco during storage according to density 259 kg m^{-3} ———, 324 kg m^{-3} — —, 388 kg m^{-3} - - - - , compared with ambient air temperature (solid bold line), for each moisture content of harvest 3, 1998.



condition of tobacco at the time of baling influences the storability of that tobacco, and that ideally tobacco should be fully ripe before harvest and properly cured after harvest. Even though decay was previously found to be positively correlated with moisture content, guidelines as to the moisture content of tobacco for safe storage cannot be given with confidence because of the variability in tobacco quality likely to be found at the time of baling.

Cigarette beetles were found in some bales throughout the three years of study. Cigarette beetles were more likely to have originated from the room in which the tobacco was stored rather from than the tobacco itself. As a result of this study it is suggested that the room in which tobacco is to be stored should be fumigated beforehand. More cigarette beetles were found close to the outside of the bales rather than the inside.

Of those three bales from the 1998 season that were stored for a longer period than most of the bales, at a moisture content of 12% and a density of 259 kg m^{-3} , there was only 10% decay found at an intensity of 3, and this decay was internal and close to the bottom of the bales. The other two bales at a high moisture content of 20% each exhibited at least 75% internal decay at a decay intensity of 9. From this example, it may be suggested that if cured tobacco is in a suitable condition when baled, it may be stored in bales for a long time.

Variation of moisture content and uniformity of moisture migration

Weight of tobacco decreased over time (Figure 2). Assuming that a loss in weight implies a loss in moisture, loss of solids is likely to occur during curing (9), all bales lost moisture while in storage. The moisture content of all bales tended to equilibrate during storage suggesting that, providing tobacco was layered in the bales and the bales were of uniform density without the presence of inappropriately cured leaf or damp foreign material, then moisture could migrate from the interior to the exterior of the bales. Most weight loss took place during the first 20-30 days. It must be noted that for those bales with decay, a minute weight loss may have occurred from the microbial activity of converting carbon compounds into energy (5).

Variation of temperature

Temperature varied inside bales of tobacco during storage (Figure 3). All tobacco temperatures were above the ambient air temperature. Ambient and bale temperatures followed the same trend, with a lag time of about two days between the tobacco and air temperatures.

Those bales with the highest moisture tended to have

Table 7. Correlation between area or volume and intensity of decay with moisture content and density of baled tobacco after storage over all harvests and years.

	Outside the Bale		Inside the Bale	
	Area of Decay	Intensity of Decay	Volume of Decay	Intensity of Decay
Moisture	-0.0033	0.2970 **	0.5585**	0.5735 **
Density	0.1135	-0.1124	0.1254	0.1923

* Denotes significance at the $P<0.05$ level with n = 91, where n = experimental unit = bales.
** Denotes significance at the $P<0.01$ level with n = 91.

Table 8. Correlations between volume and intensity of decay inside baled tobacco with area and intensity of decay outside baled tobacco after storage, over all harvests and years.

		Outside the Bale	
		Area of Decay	Intensity of Decay
Inside the Bale	Volume	-0.1381	0.3354 **
	Intensity	-0.0034	0.2571 *

* Denotes significance at the $P<0.05$ level with n = 91, where n = experimental unit = bales.
** Denotes significance at the $P<0.01$ level with n = 91.

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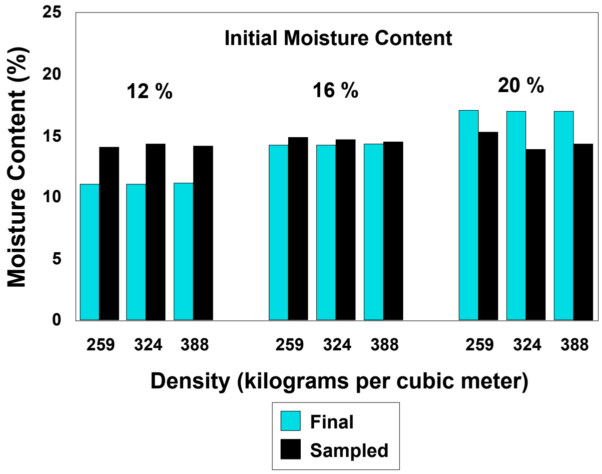
Figure 4. Moisture content measured from core samples compared with that calculated from the initial and final weight of the bales, 1997 and 1998.



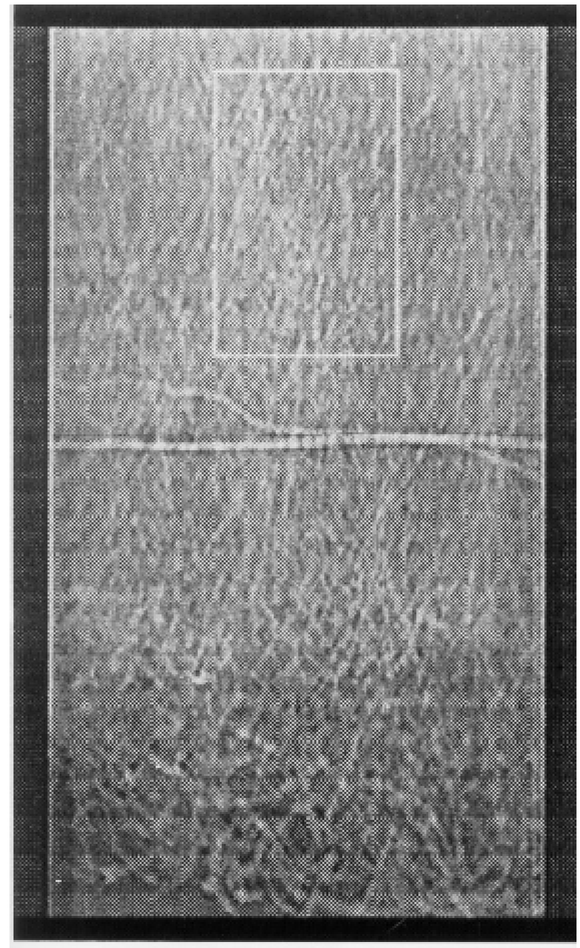
the highest temperature, although there was some variation observed according to bale and thermocouple. The differential between air and tobacco temperatures can partially be explained by the tobacco being stored in rooms having insulation in the walls. Those bales of higher moisture content experienced a greater drop in temperature when the air temperature dropped on day 292, than those of lower moisture content.

It was hypothesized that there may have been heat generated as a result of decay in those bales where decay was found. However, decay was found in bales having low as well as high temperatures. Since decay was known to originate from a center of decay, then, in order for a rise in temperature to be discernable as a result of decay, thermocouples would need to have been placed at those centers of decay. It is also suspected that the rise in temperature as a result of decay was so slight in comparison with the bulk of the bales, that it was not discernable, considering the intermittent monitoring of thermocouples by the data-logger. It was deduced from the study that the measurement of temperature was not a reliable measurement of the occurrence of decay.

Sampling moisture content

When the moisture content of the tobacco in core samples was compared with the calculated from the weight of the bale at the beginning and end of the storage period, there was a high variability in the values determined in the core samples (Figure 4). There tended to be an over estimation of moisture at the lower moisture levels and an under estimation at the higher moisture levels. As a result of this study, it may be stated that spot checks of moisture content of stored baled tobacco may not truly represent the overall moisture content of the bales because of the change in distribution of moisture in the bales during storage. Moisture migration may lead to a reduction of moisture in some parts of the bales and accumulation in other parts, especially when the movement of moisture to the external

Figure 5. Line scan of a bale section, illustrating the density variation from the outside (bottom of photograph) to the inside (top of photograph) of a bale, 1998.



surface of the bales is obstructed by, for example, folded leaves.

Nondestructive observations

Non destructive observations revealed a variation in density increasing towards the center of the bales (Figure 5). Leaf orientation within a bale was also evident. Non destructive testing was not, however, revealing as to the amount of decay within a bale.

Bale integrity

It was observed that tobacco has a small resilience for springing back to an original shape. The relaxation of the leaf allows for bales of high density to be supported with a minimum of binding material. Bale distortion was observed to be more likely with bales at the higher densities; consequently more support for tobacco in bales may be necessary at high densities.

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SUMMARY AND CONCLUSIONS

Tobacco was stored in small bales, using a factorial of three densities 259, 324 and 388 kg m^{-3} and three moisture contents of 12, 16 and 20%. Bales were of size 30 x 30 x 60 cm in 1996 and 38 x 38 x 38 cm in 1997 and 1998. The tobacco was stored for at least 7 weeks in 1996 and at least 13 weeks in 1997 and 1998. Tobacco was taken from only the upper stalk in 1996, but from lower, middle and upper positions on the stalk in 1997 and 1998. The bales of tobacco were stored in plastic bags in one room in 1996, but left unwrapped in separate rooms according to moisture content in 1997 and 1998.

Room temperature was regulated to 27°C in 1996, but allowed to fluctuate according to the seasonal temperature in 1997 and 1998. Relative humidity around the bales was moderated by the plastic wrapping in 1996, but the bales were exposed to ambient relative humidity during 1997 and 1998. During storage, temperature of the bales was monitored by means of type K thermocouples inserted in the bales and loss of moisture was monitored by changes in the weight of the bales. Following storage, the bales were examined for area or volume and intensity of decay. Nondestructive X-ray examinations of density variations within the bales were conducted on selected bales. The treatments and conditions proposed were considered a worst case scenario representing tobacco being stored during the same season or even stored from one season to the next.

Over all years and harvests, both the volume and intensity of decay on the inside of the bales were significantly ($P<0.01$) correlated with the moisture content of the tobacco in the bales, as was the intensity of the decay on the outside of the bales. Over all years and harvests, decay was not significantly ($P<0.05$) correlated with density. Over all years and harvests, both volume and intensity of decay on the inside were positively ($P<0.01$ and $P<0.05$, respectively) correlated with the intensity of decay on the outside of the bales, but not so with the area of decay on the outside. The amount of decay was correlated ($P<0.01$) with the intensity of the decay on both the inside and outside of the bales. Decay was found at all levels of moisture and density at some time during the study.

Centers of decay were found to cause decay in the immediate proximity of the center, with decay spreading from the center. Centers of decay occurred wherever moisture was found in higher concentrations than surrounding areas. Centers of decay were found to be caused by folded leaves, insufficiently cured leaves, stalks, or damp foreign matter. Considering the cross-sectional dimensions of the bales formed, the larger leaves of the middle stalk tobacco were sometimes found to be folded in the bales, restricting the migration of moisture to the edge of the bales and thus causing centers of decay to occur. When bales were placed on a solid surface, decay on the outside of the bales was often found on the base of the bales, adjacent to the solid surface on which the bales were placed. Internal decay was likely to be found towards the base of the bales.

Density of tobacco in the bales was uniform in the line of compression but varied from more dense to less dense from the center of the bales to the side.

Measuring the internal temperature of the bale was found to not be a reliable way of monitoring decay in a bale since temperature sensors may not necessarily be positioned at a center of decay where a temperature rise may occur.

Tobacco leaf was observed to have a small resilience allowing bales of high density to be supported with the minimum of binding material. However, bale distortion was more likely to be found in the bales of higher densities.

Core sampling for moisture measurement did not necessarily represent the overall moisture content of a bale, because natural moisture migration changed the distribution of moisture throughout the bale.

Based upon results obtained in this study, it is suggested that for storage: tobacco should be properly cured and carefully examined before being baled, with anything that may cause a center of decay being removed; moisture content of the tobacco should be determined before baling in order to discern if the tobacco is suitable for baling and storage, rather than risk baling tobacco with a moisture content later found to be unsuitable; tobacco should be uniformly layered in the bales to allow the movement of moisture from the interior to the exterior of the bales during storage; once baled, the bales of tobacco should receive adequate airflow around all sides including the base. Placing the bales on slats or on pallets should improve air circulation around the base; tobacco baled at higher leaf densities may require more physical support than would be required for tobacco at lower leaf densities.

Table 9. Correlation between volume with intensity of decay on the inside of bales and area with intensity of decay on the outside after storage, by harvest, for all years.

	Harvest			
	1	2	3	Overall
Outside Area versus Intensity	0.2480	0.7166 **	0.5608 **	0.4301**
Inside Volume versus intensity	0.7005 **	0.3648	0.6380 **	0.5465**
n	26	26	37	89

* Denotes significance at the $P<0.05$ level with n = 91, where n = experimental unit = bales.
** Denotes significance at the $P<0.01$ level with n = 91.

ACKNOWLEDGEMENTS

Appreciation is extended to Dewayne Dales for baling and monitoring operations, to Stevan S. Lahue, for growing and curing the tobacco, to Ed Troxell for sampling the tobacco and to Benjamin Mullinix for analyzing the collected data.

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