FINAL REPORT

MOISTURE IN COTTON GINNING REVIEW

CRDC PROJECT CTFT20

Stuart Gordon, Susan Horne and Rene van der Sluijs

November 2007

Contents

Background

The level of moisture in seed-cotton at harvest through to lint in the bale can have significant effects on the quality of fibre sold to the spinning mill. There are optimum moisture levels for seed-cotton and lint for each harvest and ginning process that allow good and efficient harvesting, cleaning, ginning, baling and safe storage. To optimise processing and fibre quality the amount of moisture taken up or lost by cotton under ambient conditions needs to be balanced with the amount of drying or moisture applied during the pre-cleaning, ginning and baling processes.

It is well known that cotton with an acceptable moisture level has improved cotton fibre tensile properties resulting in greater strength, extensibility and work-to-break values. These effects make cotton fibre more resilient during ginning and lint cleaning, and less prone to damage. Dry cotton is easier to clean but will be damaged during ginning and lint cleaning. On the other hand, cotton with excessive moisture is difficult to gin and clean, and will degrade during storage.

There are challenges associated with measuring and therefore managing moisture at each stage of the processes from harvest through to bale. Despite development of systems that measure and then allow drying or moisture replenishment to be metered onto the cotton there has not been widespread uptake. Aside from cost, the challenge for these systems is their accuracy and speed in testing. A thorough understanding of the relationship between water and cotton is essential to understand the way in which moisture might be measured by various sensors, and then for optimising the amount of moisture applied at gin processes by systems controlled by these sensors.

Introduction

Excess moisture on the crop before harvest can have detrimental effects on the modern harvest process in terms of picking efficiency and the ability to store seed-cotton safely and without degrading fibre quality. Modern ginning is also highly automated and productive, and an excess or deficiency of moisture has significant effects on processing efficiency, fibre quality and gin turn-out.

Ginning in Australia starts with seed-cotton delivered as a module to the gin. The module is opened by a series of beaters and the seed-cotton transported by air through ducts to one or a series of pre-cleaners that remove large trash, e.g. sticks, stones, unopened bolls, before the gin. If the seed-cotton is too wet pre-cleaning may be preceded by passage through a drying tower or chamber where the seed-cotton is dried with large volumes of dry heated air. Drying wet cotton improves the cleaning ability of the seed-cotton and improves classing grade. At the gin lint is separated from the seed after which it travels by air through one or two lint cleaners for further cleaning and preparation. Moisture can be added to dry cotton prior to the gin stand at either the pre-cleaning stage, although addition at this point is not usual in Australia, or after the conveyor distributor above the gin stand, which although more typical in modern gins is not standard in Australia. Lint from the gin stands is consolidated at the battery condenser at which moisture is typically added via sprays or humidified air to ease the high pressure required to press each bale and to improve gin turn-out and bale weight.

This report reviews current literature and Australian industry behaviour with regards to the management of moisture in cotton from harvesting through to the bale storage in warehouses. Its aim is to provide ginners with an up-to-date and concise collection of information on the subject of measuring and managing moisture in cotton during early stage processing and shipment.

Publications reviewed for this report include:

- A number of popular monographs on fibre and cotton fibre properties;
- Beltwide Cotton Conference Proceedings;
- United States Department of Agriculture (USDA) Agricultural Research Service (ARS) publications and project descriptions including the most recent Cotton Ginners Handbook (December 1994);

- Papers from peer reviewed journals including the Journal of Cotton Science, Textile Research Journal, Transactions of the American Society of Agricultural Engineers (ASAE), now American Society of Agricultural and Biological Engineers (ASABE), and the Journal of the Textile Institute;
- US patents describing recently introduced moisture sensors and moisture management systems;
- Trade journal articles and opinion pieces from The Australian Cotton Grower, Delta Farm Press and The Cotton Gin and Oil Mill Press;
- Marketing and technical information published by businesses that supply plant and technology for moisture measurement and replenishment in gins.

Information on Australian industry behaviour and attitudes toward moisture measurement and restoration was gathered as part of; the Best Management Practice (BMP) Gin Audits of 28 of the 34 gins operable in Australia, conducted earlier in 2007; the Australian Cotton Industry Ginning Survey conducted on 17 of the 34 gins operated in 2006; plus collected notes from discussions with growers, pickers and ginners over the last five years.

The first section describes current knowledge of the physical and chemical relationships between cotton and water and the generic methods and standards used to measure cotton fibre (lint), seed-cotton and fuzzy seed moisture. The next three sections describe the effects of moisture on fibre quality at harvesting and module building; during cleaning and ginning; and in the bale at pressing and warehousing. The last section describes the range of commercial sensors and systems currently available to measure and control moisture in cotton.

Moisture in Cotton – Fundamentals

As living plant cells, cotton fibres within a growing boll are literally full of water. Water is required to drive growth of the fibre cell and fibre staple length is closely related to the availability of water to the plant during boll ripening. When the boll matures and opens, this water is lost and the fibres lose water and equilibrate with the ambient humidity. Both constituents of seed-cotton – fibre and seed – are hygroscopic but at different levels. For example, if seed-cotton is placed in air of 50% relative humidity (rh) and 21°C, the fibres will tend to reach a moisture content of approximately 6%; the seed will tend to reach a moisture content of about 9%; and the composite mass will approach a moisture content of 8%.

In its matured, dried form nearly 90% by weight of the cotton fibre is cellulose. In fact the cellulose found in cotton fibres is the purest form of cellulose found in all plants. The cellulose in cotton fibres is mostly (88 – 96.5%) α-cellulose[1]. The non-cellulosic components (4 – 12%) are located either on the outer layers of the cotton fibre in the cuticle and primary cell wall or inside the residual protoplasm called the lumen. The secondary wall of mature fibres is primarily cellulose in its most highly crystalline and oriented form. Figure 1 shows a representation of the structure of a cotton fibre by Jefferies *et al*[2]

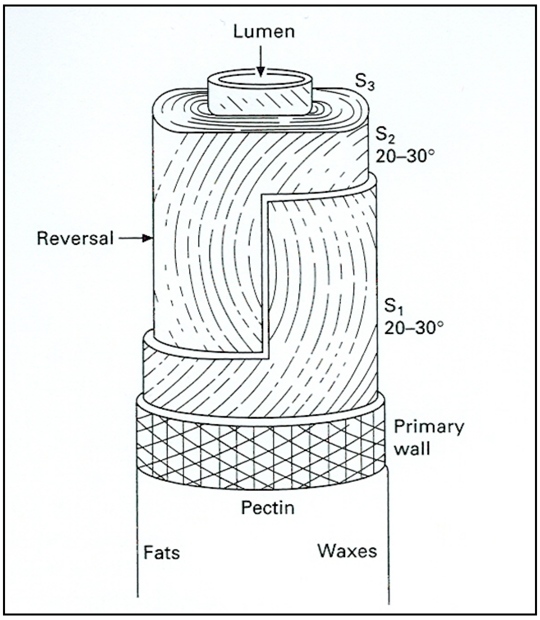


Figure 1 – Representation of the structure of a cotton fibre[2]

The basic building blocks of the cellulose chains found in cotton are β-1,4-D(+)-glucopyranose molecules linked by 1,4-glucodic bonds. Figure 2 shows the structure of this molecule. From a physical viewpoint the molecule is a ribbon-like structure of linked six-member rings each with three hydroxyl groups (OH) on C2, C3 and C6 atoms projecting out in the plane of the ribbon[3]. Covalent bonds link the glucopyranose molecules, which are further stiffened by hydrogen bonds between hydroxyl groups of adjacent chains.

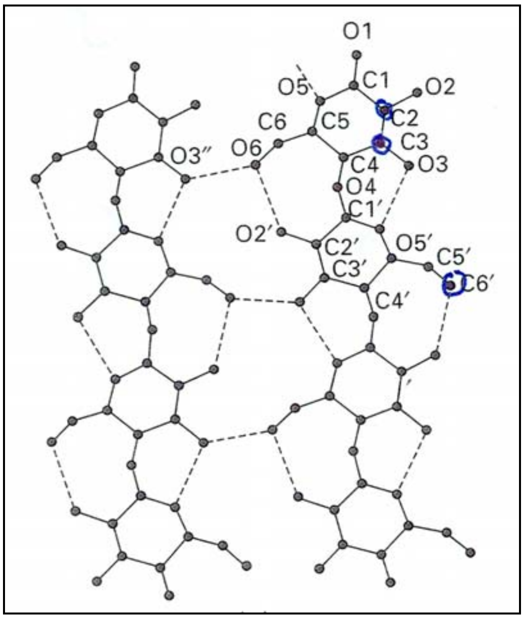


Figure 2 - Assembly of cellulose molecules in a sheet. Hydrogen bonds are shown by dotted lines. Circled carbon atoms; C2, C3 and C6, show location of hydroxyl (-OH) groups[3].

As well as providing structural stability the hydroxyl groups allow extensive inter-molecular hydrogen bonding with many molecules including water. The accessibility of water to these hydroxyl groups depends on the super-state of the crystal lattice assembly i.e., whether or not the spacing between crystal lattice planes allows penetration of water molecules. From the completely dry state, hydrogen bonds will form between hydroxyl groups that are not already linked within crystalline regions. As humidity is increased, water will be attracted to these accessible hydroxyl groups. In this respect, available hydroxyl groups will ordinarily be located on the surface of crystalline fibrils, a unit of the cellulose crystal structure. The first water molecules to be absorbed will be directly attached to hydroxyl groups. Later absorption may occur on the remaining available hydroxyl groups or form secondary layers attached to already absorbed water molecules.

Figure 3 shows the change in density of cotton with changes in regain[4]. Initially from the dry state the density of cotton increases as empty spaces (in proximity of available hydroxyl groups) within the cellulose structure fill with water. Direct absorption of water molecules results in more efficient molecular packing and gives an initial increase in density. Density then decreases as the regain increases past 4%, and layers of water molecules in effect dilute the density of the cotton cellulose structure. The relationship in Figure 3 suggests that at moisture regains in excess of 5% cotton cellulose is as full of bound water as it can be, and that beyond this level cotton contains more loosely bound water, or unbound water held by surface tension effects such as capillary action.

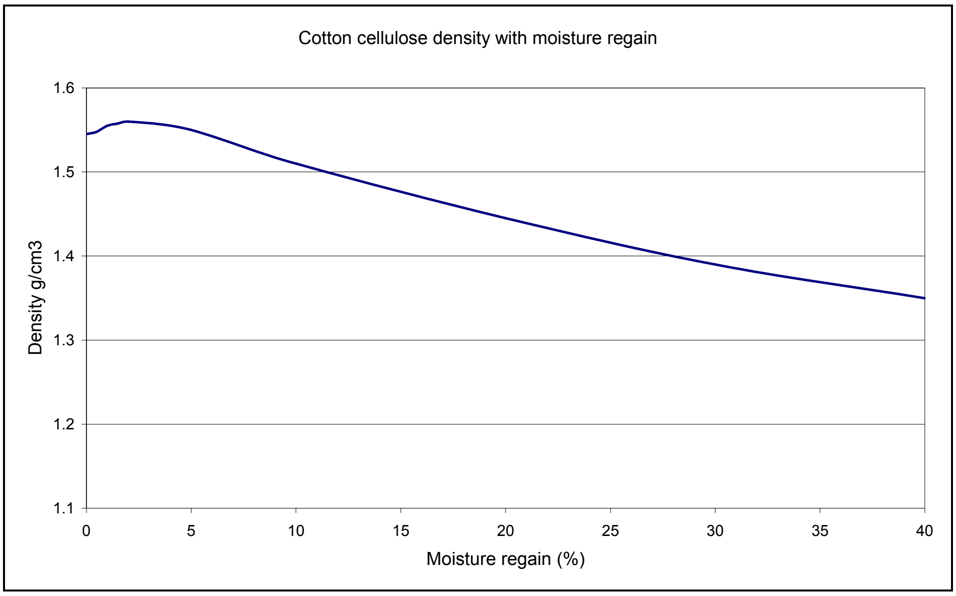


Figure 3 – Change in cotton cellulose density (g/cm^3) with moisture regain (%)[4]

The shape of the drying and wetting curves called isotherms (see Figure 4) for cotton are determined by availability of absorption sites for water molecules in the cotton cellulose structure under different rh conditions. In particular, the shapes of these curves are determined by the multi-layer absorption of water molecules within the cellulose structure. Studies by Peirce[5], Barkas[6] and French *et al*[7], are instructive in this respect. For this review the salient point is that for every combination of ambient air temperature and rh, there are corresponding equilibrium moisture contents for the seed-cotton, fibre and seed. The equilibrium moisture regain at a given rh is also a function of the barometric pressure.

The curves in Figure 4 show typical rh-regain curves for cotton fibre coming from the dry side at three different ambient temperatures. There are difficulties in making measurements close to 100% rh and the true saturation values may be higher than those shown. By an effect known as hysteresis the equilibrium regain is higher when humidity is decreased from the wet side than when humidity is increased from the dry side. In a standard atmosphere of 65% rh and 20^{o}C, the absorption regain of cotton is nominally 6 to 7%. Hysteresis increases the desorption (drying) value by 0.9%[8].

The blue dotted lines along the x-axis in Figure 4 indicate a typical rh range for the months of May through July in Australian gin and lint cleaner ducting during the day (light blue) and night (dark blue). At the time of these particular measurements no heating was being applied to cotton and no rain events were recorded. For the same period the temperatures in gin and lint cleaner ducting ranged from 30^{o}C to as low as 10^{o}C.

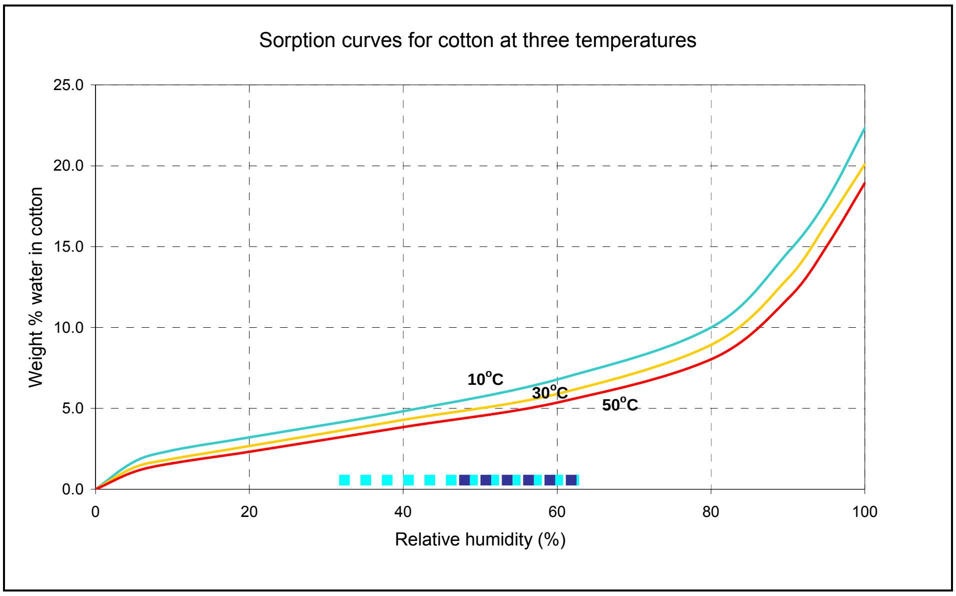


Figure 4 – Cotton moisture absorption isotherms at three temperatures. The blue lines represent typical rh ranges in Australian gin ducting in May through June

Moisture has important effects on the physical properties of cotton particularly tensile properties and other expressions normalized for weight. The increase in strength with increased moisture content is attributed to the release of internal stresses as hydrogen-bonding is weakened and to the ability of the structure to be pulled into a more oriented form without generation of internal stresses[9]. Taylor and Godbey[10] conditioned cotton and tested fibre bundle strength (tenacity) over a range of rh. At 55% rh tenacity was 25.8 g/tex and this increased to 29.1 g/tex after conditioning at 75% rh. Fibre crimp, compress-ability and torsional rotation properties are also affected by high humidity[11 12]. Moisture content also increases with trash content and fibre yellowness[13].

The glass transition temperature (Tg), which significantly affects the mechanical properties of polymeric materials and fibres is of critical importance to the processing and performance of these materials. The Tg describes the temperature (and rh) at which a material changes from being hard and glassy to one that is soft and rubbery. The Tg can be estimated in advance by means of the Fox Equation[14] (see Equation 1), which takes into account the polymer's crystallinity and the Tg of water, to calculate the temperature of the glass transition.

$$1/Tg = w_p/Tg_p + w_w/Tg_w \qquad (1)$$

Here Tg_p and Tg_w are the glass transition temperatures of the polymer and water, and w_p and w_w are the weight fractions of each in the material. The glass transition temperature of water is in the range of -124°C to -138°C. In most cases, the Fox Equation predicts a lower Tg than is observed in practice.

Whilst the Tg of synthetic fibres are well known and easily identified the Tg of natural (polymer) fibres are less well-known. A Tg in wool fibres is known, and the conditions around the Tg of wool[15] are known to affect changes in the amount of damage during processing, handling properties of yarns, such as snarling and entangling, and spirality in knitwear[16]. Little has been reported of cotton's Tg. However, recent work at CSIRO[17 18] suggests there are sound *a priori* reasons to expect a Tg in cotton and that the implications for ginning cotton could be quite profound. As per the Fox Equation the Tg in natural materials varies significantly with the amount of water in the fibre and this is determined, as per Figure 4, by the external humidity. It is proposed that keeping seed-cotton or lint near the Tg of cotton could improve the effectiveness of ginning, where the right conditions improve the mechanical properties of the fibre and reduce damage during ginning.

To gain some insight into the potential interactions between the ginning process and the fibre properties Phillips[18] made some theoretical calculations using the Fox Equation, the published Tg of dry cotton (@160°C)[19] and assuming a crystallinity of cotton cellulose at 70%. Interestingly, these theoretical co-ordinates plotted in Figure 5 coincide with measured values of 22°C and 78% rh obtained using an atomic force microscope by Maxwell *et al*[16]. The graph in Figure 5 allows any fibre moisture content at a particular temperature to be plotted and shows the position relative to the Tg. A rectangular box is plotted to show the typical range of ginning conditions likely to be encountered, e.g. a rh range in gin ducting of between 20% and 55%. Interestingly the theoretical curve falls into this region.

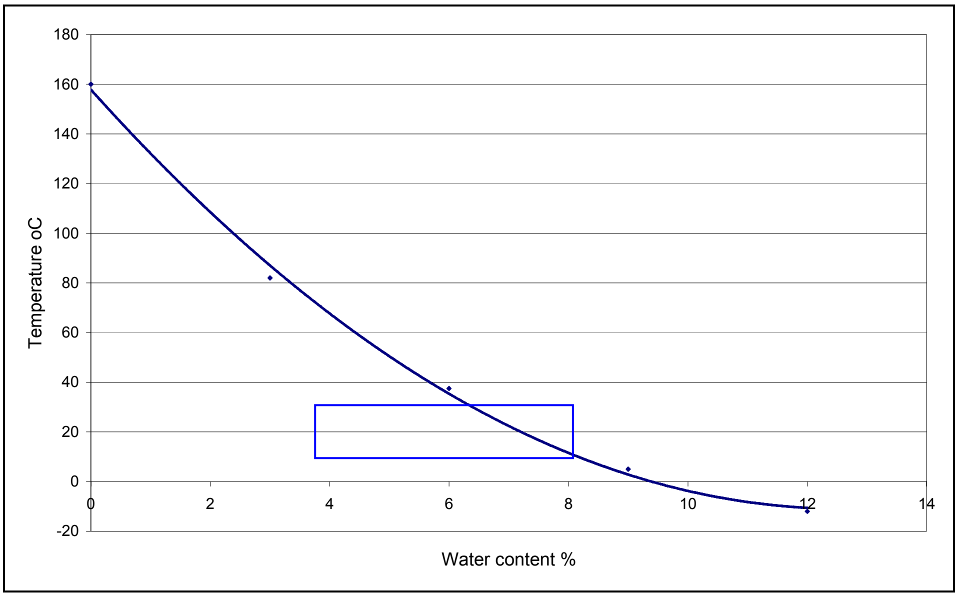


Figure 5 - The theoretical Tg of cotton as per the Fox Equation. The rectangle indicates the moisture and temperature range found in cotton during gin processing. Note this range incorporates the theoretical Tg range for cotton as calculated by Phillips[18].

Dry cotton placed in damp air for long periods will gain moisture, and wet cotton placed in dry air will lose moisture. The rate of absorption and desorption of water with change of humidity is very fast for an isolated fibre or small bundle of fibres. For denser assemblies, changes are much slower and involve complex interactions between the rate of diffusion of water molecules and the evolution and transmission of heat of sorption, and practically by the diffusion gradient between the fibre assembly and the surrounding environment (rh, temperature and air movement). Experimental and theoretical studies by Henry[20] and others are summarised by Morton and Hearle[21]. Interpolating results from these studies (see Figure 6) it can be said that fibre assemblies with the density of a commercial high density (HD) bale, i.e. around 0.4 g/cm^3, a standard half-change period of around 10 hours applies. That is, a bale of cotton when dry, at a regain of 7% and a temperature of 18^{o}C, will take around 10 hours to equilibrate to new ambient conditions. Ninety nine percent of the total change is completed in around 11 times the half-change value (~5 days). Bale weight losses experienced in Australia reflect this relationship, i.e. HD bales with regains replenished to 7.5% will lose 2 to 3 kg of weight within ½ day of storage in open, dry conditions (see Figure 6), and will lose another 2 to 3 kg if left in these conditions for periods longer than a week.

Studies by the USDA ARS show that after cotton fibre is baled, moisture transfer occurs very slowly especially at high densities. Bales at densities of 12 lb/ft^3 (0.2 g/cm^3) required over 60 days to equilibrate with the environment while bales at 28 lb/ft^3 (0.47 g/cm^3) required over 110 required over 110 days[22]. Equilibration time is also a function of the starting moisture as well as the humidity, temperature of the environment during storage and bale covering[23 24 25].

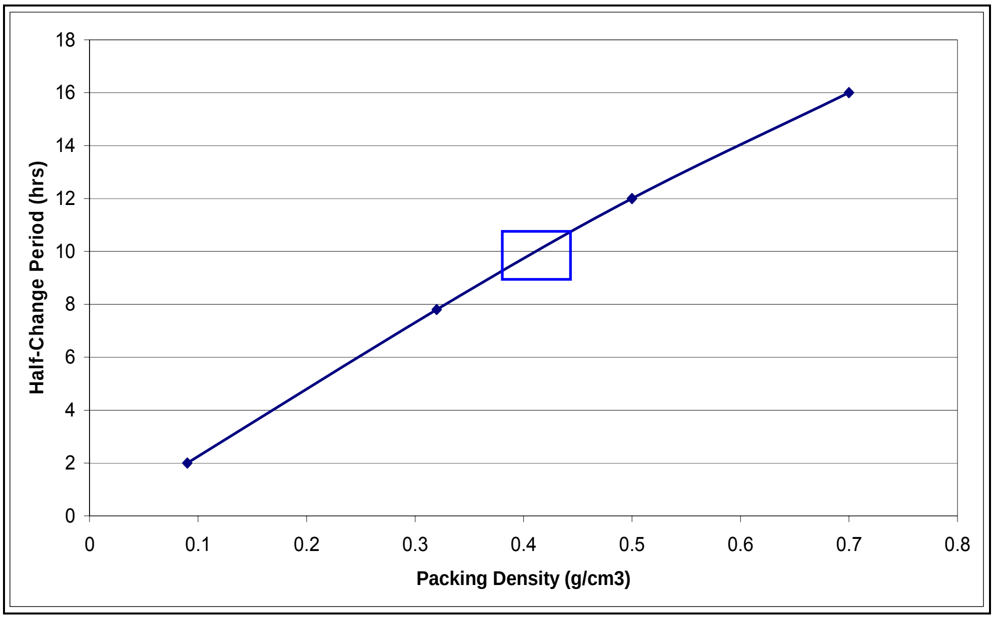


Figure 6 - The relationship between fibre packing density and the half-change period to the fibre cellulose reaching equilibrium. The blue rectangle indicates the half-change period for typical HD bales pressed in Australia[20].

Figure 7 – Typical bale storage shed for Australian cotton post-gin

Testing Moisture in Cotton and Seed-Cotton

There is no commercial regain value for raw cotton in Australian or USA trade. A value of 8.5% is specified in Rule 15 of Egyptian sales contracts and in Rule 105 of the Liverpool sales contract for Egyptian and Syrian cotton[26]. Although such moisture regain values are intended primarily for determining the commercial weight of fibre when it is bought or sold, the value of 8.5% moisture in any raw cotton is in reality difficult to achieve. The value of 8.5% is easier to achieve in processed cotton like yarns and fabrics that have been scoured, bleached, (mercerized) and/or dyed. These processes on cotton remove the fibre's wax layer, which acts as a water barrier, removed and in the case of bleached, mercerized and dyed cotton, the cellulose structure is changed such that the OH groups of the glucopyranose 'monomer' are more accessible to water molecules.

A maximum moisture regain of 11% is placed on fuzzy cotton seed sales contracts although moisture is rarely measured and no price adjustments are applied on the basis of moisture regain[27]. It is notable that other oilseeds, e.g. Canola, Linseed, etc., gain a 2% deduction in price for each 1% above the allowed moisture level when seed is destined for immediate processing is applied, or a 1.5% deduction for each 1% above the allowed level, plus a drying charge, when seed is received for storage. Modules of seed-cotton with moisture contents in excess of 12%, as measured by hand-held resistance type moisture meters, prompt immediate action from growers and/or ginners because of the potential damage that can be created by the action of microbes on the cotton cellulose.

Approaches for Measuring Moisture in Cotton and Seed-Cotton

The methods for measuring moisture in cotton lint can be classified into six groups based on the aspect of the cotton and water relationship being measured; but also on the type of cotton material being submitted for testing, e.g. compacted or loose seed-cotton, loose lint moved by air in ducting or compressed baled lint. The methods include those based on:

- Thermal drying (gravimetric),
- Chemical reaction analysis,
- Spectroscopy,
- Electrical or dielectric properties of water,
- Compression and resiliency properties of cotton lint and
- Prediction modelling of moisture based on temperature and rh isotherms.

Standard and routine methods for measuring seed-cotton moisture largely rely on thermal drying and the measurement of electrical or dielectric properties. For thermal drying methods, the liberation of volatile chemical components from the seed often confounds the ability to achieve a static 'dry' weight from the specimen, whilst the measurement of electrical properties requires calibrations determined specifically for seed-cotton. Cabrera and Mourad[28] found that the given temperature of 103°C (as per the International Seed Testing Association (ISTA) Method[29]) for the oven-dry method was not high enough to remove all moisture from seed-cotton even when left in the oven for 30 hours. However if the temperature was increased to 130°C the moisture contents were found to be equivalent to those determined by the Karl Fischer titration method, and the drying time could be reduced to 2 hours.

Thermal (Gravimetric) Methods

Thermal (gravimetric) methods involve heating a pre-weighed fibre sample to dryness for a prescribed period and then weighing the dried sample. The regain or moisture regain is then expressed as the ratio of mass of absorbed water to oven-dry mass of fibre (dry-basis). Moisture content is the ratio of mass of absorbed water to the total fibre mass (wet-basis). The equations for calculation of these expressions are listed below:

$$\text{Moisture Regain (\%)} = [(M-D)/D] \times 100 \qquad (2)$$

$$\text{Moisture Content (\%)} = [(M-D)/M] \times 100 \qquad (3).$$

Where: M = mass of (wet) specimen as received and D = mass of oven-dried (dry) specimen

Both values are usually quoted as percentages and both quantities are often used inter-changeably leading to confusion about the quantities expressed. Measurement of moisture in this way is described in standard methods for determining the moisture content or regain of cotton fibre. Best results are obtained in physical laboratories where drying ovens and weighing scales are routinely calibrated and where the tared weight of drying vessels can be accurately determined. Table A lists some currently available commercial laboratory-based thermal (drying) systems.

Chemical Reaction Methods

Chemical reaction analysis for moisture content involves a colorimetric or volumetric titration measurement of moisture that has been extracted from the fibre and/or seed. An example of a chemical reaction method is the Karl Fischer[30] titration measurement of moisture content, which was originally based on a reagent containing pyridine (C_5H_5N), iodine and sulphur dioxide according to the Bunsen Equation without the excess of water. Equation 4 shows the original formulation of the reaction:

$$2\,H_2O + SO_2 + 2\,C_5H_5N + I_2 \rightarrow H_2SO_4 + 2\,HI\,C_5H_5N \qquad (4).$$

The reaction is carried out in a suitable alcohol, typically methanol, although a number of suitable alcohols exist. The premise of the reaction in methanol was further elucidated by Smith and Bryant[31] who found that all of the water is extracted from the sample and that it combines quantitatively with the reagent and alcohol to form pyridine iodide (C5H5N.HI) and pyridinium methyl sulphate (C5H5.HI.SO4CH3). Water and iodine are consumed in a 1:1 ratio in this reaction so that once all of the water is consumed the presence of excess iodine can be detected volumetrically by titration. The most important advantage of Karl Fischer method over conventional thermal drying methods of moisture determination is its specificity for water. However, because the fibre and/or seed specimen must be ground to powder in preparation for the test, the test is limited to examining specimen moisture under the conditions that the test is carried out. In this respect the test is best for analysing the relative moisture content of substrates that are of significantly different molecular make-up. Further, while the Karl Fischer method is technically accurate, it is a time consuming test that requires very careful laboratory and sampling technique. It is noted also that the original pyridine based reagent for this reaction is odorous and toxic to operators; although less malodorous and toxic reagents are now available.

Spectroscopy Methods

Spectroscopy methods for moisture determination involve the use of a spectroscope to measure the amount of electro-magnetic energy of particular wavelengths absorbed (or reflected) by water molecules in different bonding states with the sample. The quantity of moisture is measured by the intensity of the moisture absorption (or reflectance) spectra. The most used region of the electro-magnetic spectrum for this application is the near infrared (NI) region, i.e. between 700 nm – 2500 nm. In particular the 1490 nm and 1930 nm wavelengths are known to be strong absorption regions for the OH group in water, and are often referred to as moisture bands. For cotton, spectral differences with changing moisture are observed at 1490 nm, although a significant and distinct absorbance due to cotton cellulose itself is also observed at this wavelength. At 1930 nm, the strong OH absorption is due to the moisture on the fibre and not cotton cellulose itself. The OH absorption at 2170 nm also correlates strongly with the moisture content of the sample. Figure 8 shows a typical NI absorbance spectrum of cotton. Other parts of the infrared region with longer wavelengths (> 2500 nm) also give information about moisture, although these are less sensitive in measuring the specific absorption energies of cotton cellulose and water molecule bonds.

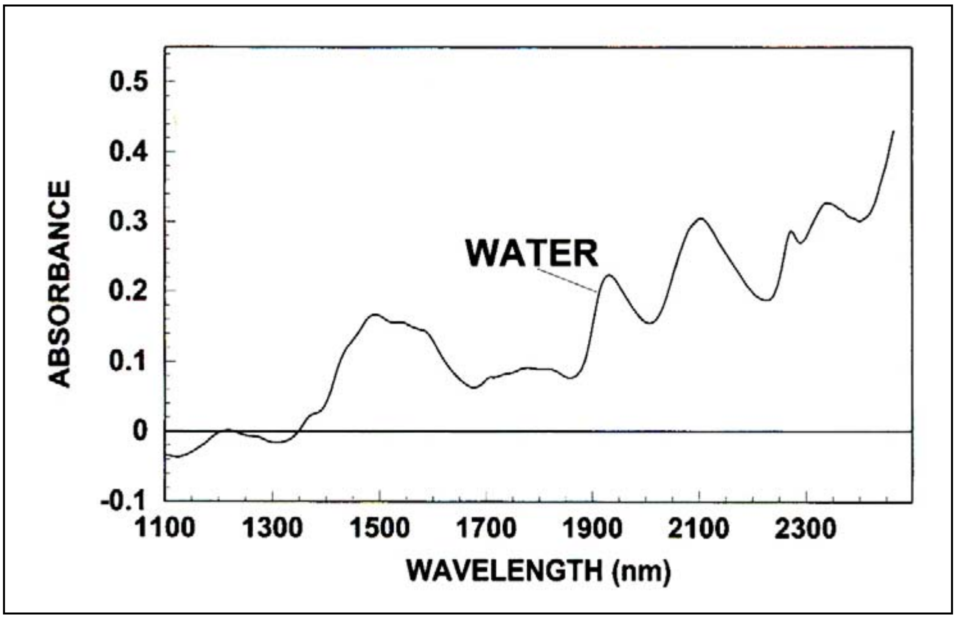


Figure 8 – Typical near infrared absorbance spectrum for cotton lint showing main moisture band at 1930 nm[32]

Whilst NI spectroscopy is used routinely to measure moisture and other chemical and physical attributes in a wide range of agricultural commodities, e.g. in the wheat grain industry NI spectroscopy is used to assess moisture, protein and a range of other quality attributes, its application to cotton measurements is limited by its inability to penetrate the sample more than about a 1 mm depth, and the chemically consistent nature of cotton. As well, to ensure precision and accuracy specimens for NI analysis need to be compressed to a consistent density during analysis[32]. Further, the inability to apply sensitive (and expensive) spectroscopic instruments into the rugged cotton harvesting, ginning and warehousing environments also limits their application.

Anthony[33] tested infrared moisture meters in research and commercial gins from 1988 to 1990. Each season an average of 16,500 bales were tested for moisture using the sensors. The results showed significant relationships between sensor readings and reference oven moisture tests with correlation coefficient (r^2) between 0.73 and 0.78. Error observed in the relationships was put down to inconsistent sample presentation and drift in the instrument readings. Anthony thought updating the calibration as well as subsequent validation procedures of these instruments would improve the potential utilization of the instruments. Thomasson[34] tested the NI absorption ability of standard silicon chips found in black-and-white video cameras to measure moisture in seed-cotton and lint samples through a micro-gin. The test was done to investigate whether or not colour and trash could be measured at the same time as moisture thereby eliminating the need for a second instrument; and to determine whether less-expensive silicon sensors could substitute for the more expensive lead-sulphide or platinum-silicide sensors used in NI spectroscopes. Whilst the silicon-sensor could predict oven moisture its accuracy was not good enough for the purposes of instrumentation. Thus while it is technically feasible to make infrared and NI moisture measurements in the gin, generally from accuracy, practicality and cost perspectives these methods of measuring moisture are not applied.

Electrical Methods

Electric methods that measure moisture in the lint or seed-cotton specimen based on changes in electrical charge measure the moisture absorbing capacity of cotton and to some extent the presence of mineral salts. Electrical charge in these methods is typically measured in terms of resistance or permittivity (measured in relation to micro and radio-wave transmission). Conductivity is low (resistance is high) in very dry cotton but is reasonable in cotton with some moisture. As such static electricity is not generally a big problem in cotton except when it is very dry. Cotton shows a linear decrease in the log of specific resistance (Rs) between 10% rh and 80% rh[35]. Resistance meters are used widely to measure moisture in seed-cotton or lint samples pre, *in situ* and post-gin, as are microwave and radio-wave transmission sensors, which respond to the much larger (relative to dry cotton and empty space) dielectric of water in denser seed-cotton and lint samples. Capacitance based sensors, which measure the amount of charge stored for a given electrical potential, are used in textile and raw wool processing applications but have not been extended to ginning.

Figure 9 shows the methods of moisture determination used by Australian ginners. The results come from the recent gin BMP audits carried out by CSIRO[36]. The Figure shows that nearly all gins use some electrical method of moisture determination at all three 'stages' of ginning. Microwave systems were used to determine moisture in modules in 50% of gins and nearly 80% of gins used a microwave system to measure bale moisture. Hand-held resistance instruments were most used (55% of gins) to determine moisture levels during ginning. The frequency with which hand-held resistance sensors are used is not known as records are not usually kept. The remainder of gins employed fixed in-line resistance instruments to test moisture during ginning. Only a small percentage of gins are able to provide historic records of bale moisture.

A range of opinions is held about how good the results are from each of these sensors. The predominate view of resistance-based sensors is that they give satisfactory indications of wet or dry cotton, but their accuracy in the significant 5% to 8% moisture range is not good enough for reliable metering of moisture or drying energy (gas). The opinion of microwave sensors employed for module and bale moisture measurements is largely good, although as discussed later in this section there are now commercial pressures to manage bale moisture and in particular the distribution of moisture in bales more closely.

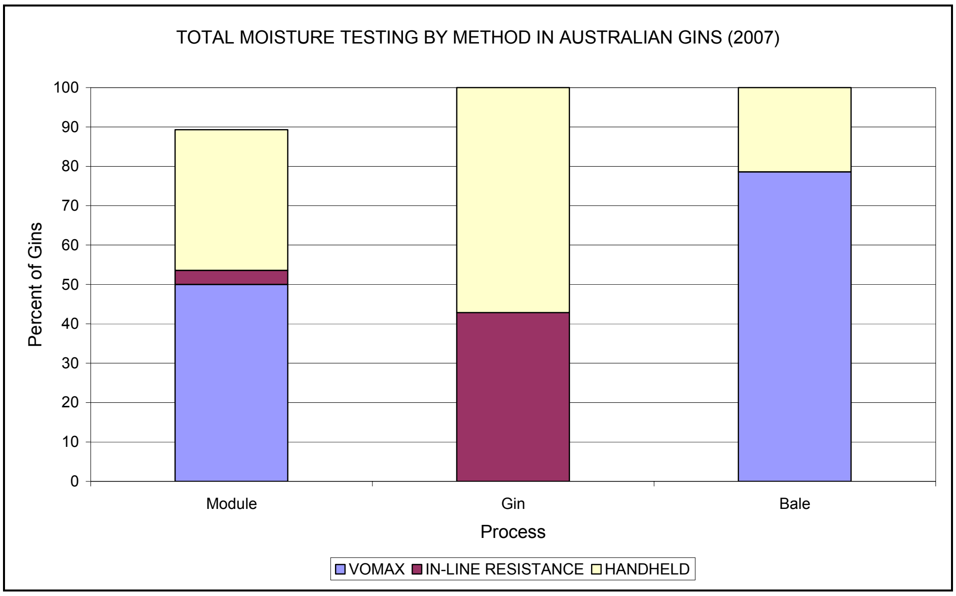


Figure 9 – Electrical methods used by Australian gins to measure moisture at the module, in the gin and at the bale.

Resistance-based Methods

Resistance-based moisture sensors do not work well when water droplets are sprayed directly on the surface of the fibre. The combination of absorbed and surface moisture can cause errors in resistance-based moisture sensors, as the conductive effect of surface moisture and contaminants distorts (increases) the measurement. Nor do these sensors work well when moisture content is very low (< 4.5%)[37]. As per Hearle[35] the Rs at low moisture contents becomes very large, with a converse reduction in current. A consequence is that resistance-based sensors need specially designed circuitry in order to manage the very wide range of currents produced between test electrodes subject to a normal range of moisture contents, i.e., 4% to 10%. It is also the case that distortion and noise in measurements are amplified when the specimen is not applied correctly or consistently between or around electrodes.

An examination of some currently available portable cotton bale moisture meters was made in 2006 by the USDA ARS[38]. The investigation found that the moisture content measured by each meter was consistently different from the oven-based moisture content. The authors suggested a constant offset value could be applied to improve the measurement accuracy. In looking at the relation between sensor accuracy and the economic incentive to measure moisture accurately Pelletier[39] found that if a sensor was known to have an accuracy of only ±1.5% moisture, a typical accuracy specification for the current (US) industry standard resistance sensors when used in rapidly conditioned cotton the control system should be set 1.5% below the target range in order to avoid packaging bales with excess moisture.

Valco *et al*[40] noted that when any type of portable moisture meter is used reading accuracy and precision can be improved by:

- Following the manufacturer's recommendations,
- Using uniform, homogeneous samples of about the same weight,
- Wearing gloves to prevent moisture transfer from hand to sample,
- Placing each sample in the measuring cup immediately to minimize moisture change in each sample,
- Compressing each sample uniformly with the same amount of pressure applied each time,
- Checking instrument calibration and
- Replacing the battery or connecting mains power when needed.

The USDA ARS have worked towards development of more accurate resistance-based sensors. In 2004 Byler[41] reported a resistance-type moisture meter that could make measurements in less than 1 second by measuring a set direct current across the sample. Test precision was dependent upon keeping the voltage and timing of the test consistent, and sample density constant. Regression analysis showed the standard error in predicting moisture using this instrument was ±0.20% over the range 4.1 to 8.7% (wet basis). However, there was no development of this sensor beyond the laboratory[37]. In 2006 Byler[42] introduced a new portable bench-top resistance instrument based on the successful design of the sensor employed in the 'Intelligin' system[43], which was developed earlier by the ARS[44]. Like the 'Intelligin' sensor features of this instrument were the application of a standard compression to the specimen and use of multiple electrode sensors. Byler reported an accuracy of ±0.25% within a moisture range of 4.3 to 10.2% moisture content. The instrument has been licensed but not widely sold. Lists of commercially available hand-held and in or on-line resistance-based moisture meters for cotton appear in Tables B and D at the end of this report.

Microwave Methods

Whilst techniques involving the transmission of microwaves (electro-magnetic radiation with wavelengths between 10^{-3} and 0.3 m) through materials to determine moisture have been known for 50 years[45] it was not until the late 1990s that a number of technical and cost difficulties associated with their application were overcome[46]. One issue particular to cotton bale moisture determination has been the alignment of the microwave transmitter so that the microwave energy from the transmitter to the receiver could pass fully through a bale in the alignment direction of the compressed layers that form a bale. The boundaries of these layers have different densities and as such can cause the microwave energy to be internally reflected or scattered, affecting the accuracy of the predicted result[47, 48]. The VOMAX microwave system[49], which is built in Australia and widely used here and the USA, claims to overcome this problem by directing and controlling the transmission and reception of microwave energy orthogonally through layers of the bale, rather than being restricted to the direction between the boundaries of one layer. Another aspect of the VOMAX microwave system is the range of frequencies transmitted; the range transmitted is noted to fit well with the geometry of the transmitter and receiver. Other manufacturers of microwave moisture sensing technology applicable to cotton are listed in the Table C at the end of this report.

Existing microwave systems have a disadvantage in that they average moisture over large sensing areas and as such miss localized high moisture areas, i.e. areas within the bale that might be in excess of 7.5%, which the USDA Commodity Credit Corporation (CCC) that manage the Market Assistance Loan Program (a reserve price scheme for US cotton growers), now hold critical. Recently Pelletier[50] examined a method of providing a moisture profile of the bale using new tomographic microwave imaging technique, although earlier in 2005 Uster Technologies introduced a bale moisture measurement system called the 'Final Bale Moisture' (FBM) system to measure the moisture profile of a bale[51]. The FBM relies on measuring the transmittance of ultra low frequency radio-waves (of 1 kHz) through a bale[1]. The value of both these systems is their potential ability to provide ginners with feedback on the amount and distribution of moisture being applied at the battery condenser and lint slide. By way of example, Figure 10 shows the moisture profile of bales treated with humidified air and one and two spray nozzles as measured by the FBM system. Whilst the average moisture content of the bale treated with two sprays is less than 7.5%, the FBM measured a number of points in the bale in excess of 8%. According to information presented in the section on the addition of moisture to bales, wet spots in excess of 7.5% are likely to cause fibre quality degradation[129]. Information about moisture variation in the bale has not yet been deemed critical by Australian ginners and merchants, although its value to high throughput gins using atomizer spray systems to replenish moisture in dry bales is obvious. The company that manufactures the VOMAX instrument has indicated that measurement of bale moisture variation is also possible using their microwave transmission system[52].

[1] There is some question over the sensitivity of radio-wave lengths that exceed the specimen (bale) dimensions, although this has not been tested in literature.

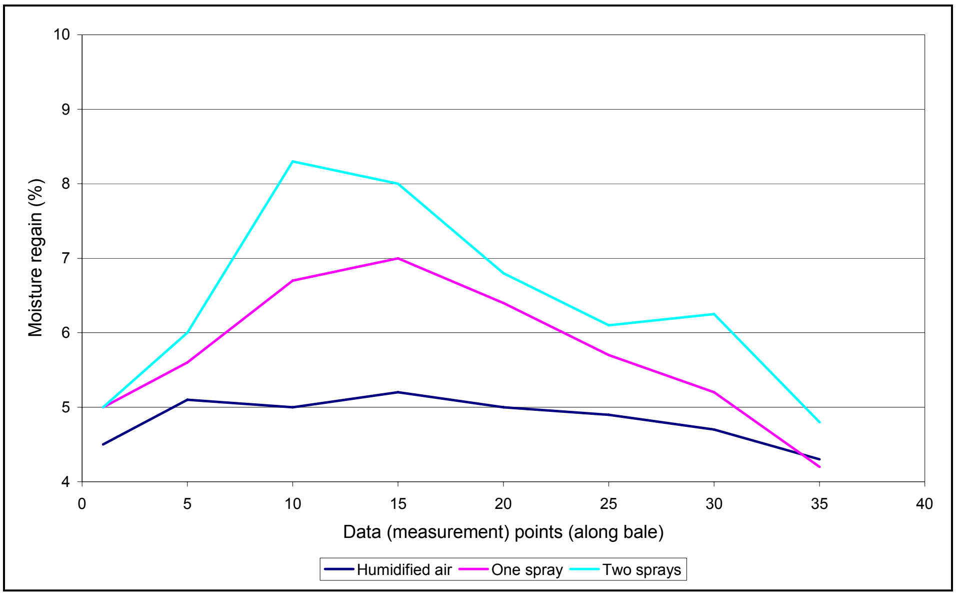


Figure 10 – Bale moisture profile in three bales subject to different moisture restoration treatments as measured by Uster Technologies FBM system[51]

Compression Methods

Measurement of the pressure differences required to compress dry and wet cotton bales has also been used to predict the moisture content of cotton in bales. As described earlier in this review moisture affects the compressibilty and resillience of cotton. More recent work in this area followed earlier investigations by Anthony and McCaskill[53] and Anthony[54]. In 2003 Byler and Anthony[55] reported a hydraulic-based system that could predict bale moisture in the range of 3.3 to 7.9% with a standard error of 0.4% for prediction of oven-based moisture values. Measurements were based on bale weight, bale volume and the measured pressure once the bale volume had been reached. Issues with this type of measuring system would be the expected restrictions in transferring one compression calibration to other presses that have different geometries, compression ratios and work in different micro-climates; each of these variables having a significant impact upon the original calibration coefficients.

Prediction Modelling Methods

Mathematical models that predict seed-cotton moisture content using the air temperature, air mass flow and seed-cotton mass flow to account for heat transfer from the conveying air, heat added to the room and the seed-cotton, and the heat added to the water in the seed cotton have been developed. A model calibration by Gillum and Armijo[56] involved two conditioning rates, two mix point temperatures, and two moisture contents. The model had a satisfactory correlation coefficient (r^2) of 0.80 when regressed against actual seed-cotton moisture content, but did not perform well at moisture contents of less than 6%, a level at which most cotton gins operate.

Standard Methods for Moisture Determination

The following section describes the most used standard reference methods for determining moisture in lint and seed-cotton. For accuracy and precision these procedures are best carried out under prescribed laboratory conditions. Their results provide reference data against which any instruments for measuring cotton moisture can be calibrated.

Two organisations have a major role in the administration and publication of standards for testing fibre and textile materials. These are the American Society for Testing and Materials (ASTM), which has co-ordinated and published standards for over 100 years and the International Organization for Standardization (ISO), which is the world's largest developer and publisher of international standards. The ISO heads a network of national standards institutes from more than 150 countries. A Central Secretariat in Geneva, Switzerland coordinates the ISO system.

Moisture Determination - Lint

The ASTM Standard designated 2495-07[57] describes the determination of the amount of moisture in cotton by oven-drying and is applicable to raw cotton, cotton stock in process, and cotton waste. It is also applicable for determining moisture in blends of cotton with other fibres, and to seed-cotton, although as per Cabrera and Mourad[28] and experience at CSIRO[58] the prescribed oven temperature for this Standard does not readily remove moisture from the seed component. The Standard is accepted by researchers as the laboratory-based method to determine cotton moisture content using an oven drying method. It is often used to calibrate and compare new moisture measurement instruments.

The ASTM Standard covers the drying and weighing of specimens under a set of standard conditions. Alternative procedures for weighing the dried specimens are given; one procedure uses an oven balance (an oven with a balance *in situ*) whilst the other uses a desiccator to cool the specimen before weighing after each drying period. In the Standard lint specimens must be at least 5 g and weighed to within ±0.01 g**.** Specimens are dried in an oven at 105°C ±2°C for at least 1 hour or until the change in mass between successive weighing at intervals of at least 15 mins is less than 0.1% of the specimen mass. The difference between the original mass and the oven-dry mass is calculated in percent, either as moisture content or moisture regain – see Equations 2 and 3.

Using the desiccator method specimens are dried in (glass) weighing containers that are opened whilst in oven and closed prior to withdrawing from the oven. Samples are cooled to room temperature in desiccators before being weighed in their weighing containers to nearest 0.01 g. Defined cooling periods need to be determined to ensure consistent mass readings between samples. It is noted that hot or warm, closed weighing containers are affected by larger buoyancy factors than cool samples[59], as a result of lower air and sample densities.

It is important to note that very dry cotton may absorb as much as 0.7% moisture from the standard atmosphere during the first 30 secs after the container is opened and exposed to ambient conditions. However, cotton containing at least 3% moisture will not change more rapidly than 0.1% during exposure to air at ordinary temperature and humidity.

Moisture Determination - Fuzzy-Seed

Seed moisture is a primary factor influencing seed quality. Nonetheless, the Rules for Testing Seeds from the Association of Official Seed Analysts (AOSA) do not include standards for seed moisture determination. The International Seed Testing Association (ISTA) makes provisions for seed moisture testing of several crops and includes cotton in the category for which an oven drying temperature of 103 ±1°C for 17 ±1 hours is recommended[60]. An ISO standard[61] (ISO665:2000) exists for determining the moisture and volatile matter content in oilseeds, which is applicable to ginned cotton seeds, but not seed-cotton. Other versions include those described by British[62] and German Institute Standards[63]. In the ISO Standard the moisture content of a test specimen is determined, either on the material as received (pure seed and impurities) or, if required, on the pure seed alone, by drying at 103 °C ± 2 °C in an oven at atmospheric pressure, until a practically constant mass is reached as per the Standards for cotton fibre moisture determination. Specimens should be prepared according ISO664:2000, which describes extraction of oils and volatiles in methanol from the specimen before grinding, and then tested by drying according to ISO665:2000.

CSIRO Rapid Regain Test

The 'Rapid Regain' Tester (RRT) is a rapid drying device developed at CTFT[64]. It was designed to be operated on the mill floor and was initially developed to test wool regain. Its main advantage is that it provides readings of regain in less than six minutes for most applications. It was also initially developed to be a direct reading instrument so that there was no weighing-out of the sample and no calculations were necessary. The RRT uses a 3-stage fan to force air up a thermostatically-controlled heating column terminating in a socket for attaching the perforated specimen container. For testing purposes the temperature is thermostatically controlled to 110°C.

Recent research at CTFT compared results from the RRT with test results determined by ASTM D2495-07. Good correlations in the moisture regain of raw cotton samples conditioned to various regains were found (see Figure 11). Conditioned raw cotton samples were dried over 15 minute intervals in the RRT set at 110^{o}C. Samples dried in RRT drying containers were transferred quickly to desiccators and cooled to room temperature before being weighed in their drying containers to nearest 0.01 g. Dry weights were recorded at intervals of 15 minutes drying time until the weight change between two successive weightings, as per ASTM D2495-07, is less than 0.1% of the sample mass.

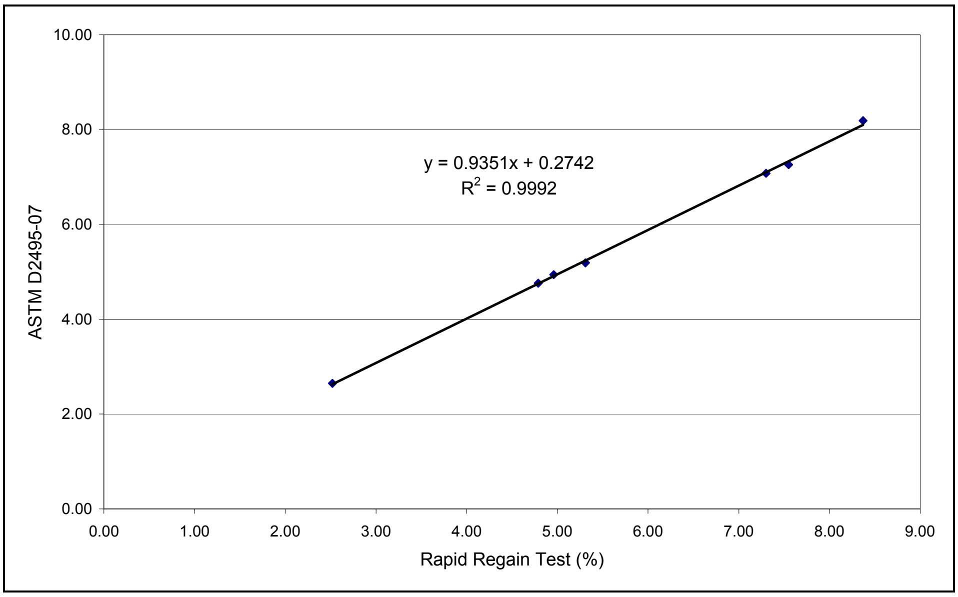


Figure 11 – Comparison of cotton moisture values determined by ASTM D2495 and RRT methods

Table I – Summary table of moisture measurement methods

Parameter	Thermal	Chemical	NIR	Resistance	Dielectric	Capacitance[2]
Speed	> 30 mins	> 2 hrs	< 1 min	< 1 min	~ 1 min	1 sec
Specimen	5 – 50 g Whole	< 10 g Whole	5 – 50 g Surface	5 – 500 g Selected	> 40 kg Part bale/module	> 40 kg All material in duct
Accuracy	Standard	Very good	Depends	Depends	Depends	Depends
Maintenance	Minimal	High	Some	Minimal	Minimal	Minimal
Application	Lab	Lab	Lab/on-line (on-duct)	Lab/hand/on-line (in-duct)	Lab/on-line (module or bale)	On-line (whole duct)
Portability	Poor to fair	Very poor	Poor	Very good	Fair	Poor
Expense	< $5K	$$$ for lab set-up	> $20K	< $3K (hand) > $20K (on-line)	~ $7K (lab) > $25K (on-line)	Not available commercially
Other Impacts	Strict observation of standard procedure required for accuracy	Specimen must be tested under equilibrium	Surface only measurement; Instrument must be calibrated with historic range of samples and moisture contents	Surface contaminants alter reading; diminished sensitivity for very wet or very dry samples; calibration required	Position of sample to transmitter and antennae must be consistent; calibration required	Position of capacitance plates must be firm; calibration required

[2] Capacitance as a moisture sensing technique is listed here *in lieu* of industrial trials of CSIRO's new capacitance sensor duct in 2008

Moisture in Harvesting and Module Making

It is essential to consider the effects of atmospheric conditions, particularly relative humidity, when harvesting seed cotton. According to the literature[65] [66] [67] moisture in modules is typically viewed in two ways; as being too high due to dew or rainfall events, or as being acceptable for storage and later ginning. Seed-cotton moisture above 12% is viewed as the cut-off, above which cotton is too wet to harvest. Above 12% harvesting efficiency is reduced as a result of poor doffing efficiency, i.e. no flow out of the basket. Spindle twist whereby the fibre becomes twisted around the spindle and is unable to be removed also arises when the moisture level of the harvest increases. The result of spindle twist creates quality problems although there are no formal research results linking the percent moisture at harvest to spindle twist problems in the mill.

Moisture is also important from the perspective of seed-cotton storage in modules. The effect of module moisture on fibre quality has been an important area of research and management, particularly in the USA by the USDA ARS. Studies have been conducted on the moisture content[68] [69] [70], length of storage[71] [72], amount of high-moisture foreign matter[25], variation in moisture content throughout the stored mass[73], initial temperature of the seed cotton[20], temperature of the seed cotton during storage[74], weather factors during storage (temperature, relative humidity, rainfall)[75] [76], and protection of seed-cotton from rain and wet ground[77]. Whilst there have been no equivalent formal studies conducted in Australia on the effects of prolonged and elevated moisture in modules, the guidelines given by US researchers (see above) are by-and-large applicable to Australian conditions.

In 1964 Parker and Wooten[78] formally documented that increased seed-cotton moisture levels at time of harvest and during storage before ginning had an adverse effect on cotton colour and grade, although the effects of moisture had surely been assessed before this time. Lalor *et al*[75] showed that seed-cotton harvested and in modules above 13% moisture content (wet basis) would probably suffer lint quality degradation during storage, while seed cotton in modules and stored below 12% moisture should retain its inherent quality. Some colour degradation (spotting) occurs at a moisture level above 11%. High moisture content causes yellowness to increase sharply at levels above 13% to 14%, especially when the storage period exceeds 45 days[79].

The colour degradation seen in moist or wet seed-cotton is caused by micro-organisms whose activity is propelled by moisture and warmth. Both temperature rise and maximum temperature are important indicators of microbial activity; temperature rises of 11°C or more, or temperatures above 49°C indicate the need for immediate ginning to minimize quality degradation and the potential of fire[75]. Sustained heat generation after harvest is caused by biological fermentation, which is reliant on oxygen and living micro-organisms and works best at moisture contents between 12% and 20%; and then by exothermic processes that cause sharper increases in temperature. Yellowing is accelerated at high temperatures. The rate of lint yellowing increases sharply at moistures above 13% and can increase even after the temperature of a module drops.

Typically cotton is too moist for harvest at dawn in Australia, although the recent warm dry seasons have meant pickers have started earlier and finished later. It is noted by some pickers that moisture monitoring needs to be more frequent at each end of the day, as the change in moisture can be quite abrupt increasing from a low of 4% to 6% within ten minutes[80] as night and dew point temperature fall. Dew point temperature is the temperature at which water vapour in air condenses (assuming air pressure remains the same). Figure 12 from shows the lint moisture in seed-cotton modules through the course of one day with conditions similar to those experienced in Australia. It is noted that module moisture in Australia over the last few years has rarely exceeded the 10% mark indicated in Figure 12 and that, by and large, modules have been delivered to gins very dry.

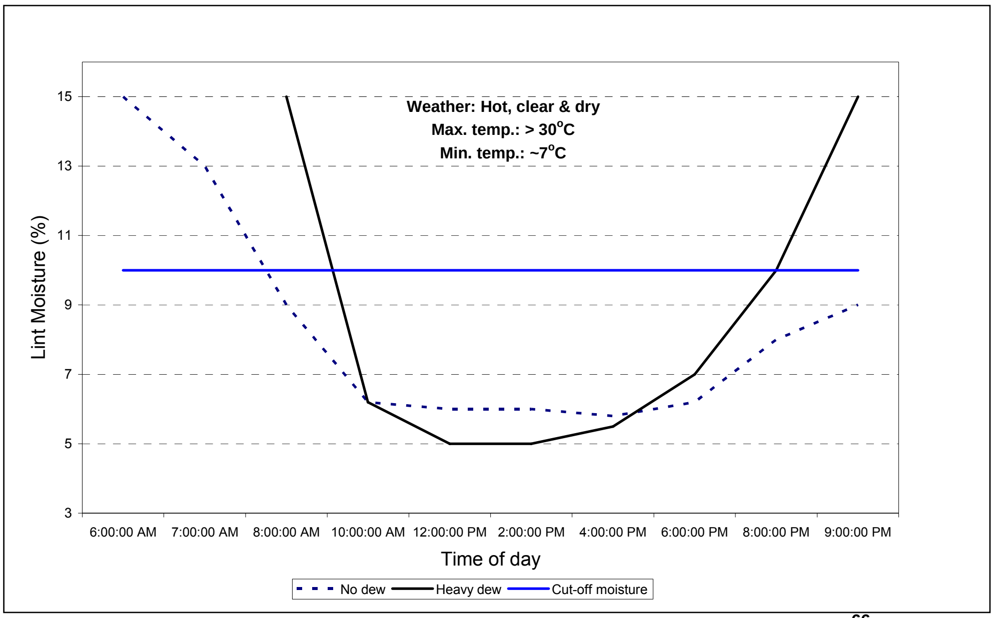


Figure 12 – Lint moisture over a day during harvest – adapted from[66]

Monitoring moisture in seed-cotton prior to harvest is typically done using a hand-held resistance type moisture meter. Sampling and testing this way is problematic because of compromises in sample selection and preparation of the specimen for testing. No specimen selection standards exist and as such the test results from these analyses are notoriously variable. Personnel using hand-held meters are advised by the instrument manufacturers to use the average of 2 to 3 tests, each time using a newly picked specimen.

Sensors for monitoring moisture on-line during harvest from pickers have been investigated. Anthony and Byler[81] applied resistance-based meters in a spindle picker, using a paddle sampler to obtain specimens for testing, and the tramper of a module builder. Test results were recorded in the range of 5% and 12% and correlated with results from the oven-dry method and a laboratory resistance-based sensor. Whilst offsets in the relationship between the reference and test data and the limited range moisture contents tested were observed, the authors declared the potential for these sensors to be used by industry in 1999[82]. However since this time there have been no further reports on its application into industry. Ag Leader Technology in the USA, advertise a radio-frequency moisture sensor as part of their 'PF-Advantage' tool on pickers and harvesters although no information on the sensor or its accuracy and precision is noted in marketing publications[83].

The Australian company VOMAX Pty. Ltd., manufactures a microwave sensor for monitoring moisture in modules on module buggies[84]. This sensor is used by a number of gins in Australia and the USA to monitor module moisture into the gin. The use of microwaves in this application is dependent upon the test material (the seed-cotton) being dense enough to attenuate transmission of the microwaves. This dependence on specimen density removes the applicability of microwave radiation for on-line moisture analysis of seed-cotton in picker baskets or in gin ducting where the material is looser and less dense. The advent of the new pickers that condense seed-cotton to densities similar to current modules, e.g. the Case International Harvester Module Express, might allow microwave sensing to be used in this type of application.

The safe storage of seed-cotton as modules is contingent upon making good quality modules, i.e. modules of a uniform density with straight sides, and then keeping these dry by means of well fitted good quality tarps and raised earthen beds that allow good drainage after rain events. Clean, dry and well formed modules can be stored indefinitely without deterioration. Wet-bottomed modules are a problem. Warehouse buildings provide maximum protection and are known in some cotton growing countries however the cost of this type of infrastructure for modules is prohibitive and the handling logistics are severely impractical for Australia and US gin operations.

Moisture during Ginning

Figure 13 illustrates the typical gin processes in an Australian gin. Modern gins are highly automated and productive systems that incorporate many processing stages besides the removal of lint from the cotton seed. Seed-cotton delivered in modules is opened by a series of beaters and transported by air through ducts to one or a series of pre-cleaners, which remove large trash e.g., sticks, stones, unopened bolls, before the gin. If the seed-cotton is too wet pre-cleaning may be preceded by passage through a drying tower or chamber where the seed-cotton is dried with large volumes of dry heated air. Drying wet cotton improves the cleaning ability of the seed-cotton and improves classing grade. At the gin lint is separated from the seed after which it travels by air through one or two lint cleaners for further cleaning and preparation. Moisture can be added to dry cotton prior to the gin stand at either the pre-cleaning stage, although addition at this point is not usual in Australia, or after the conveyor distributor above the gin stand, which although more typical is not standard in Australia.

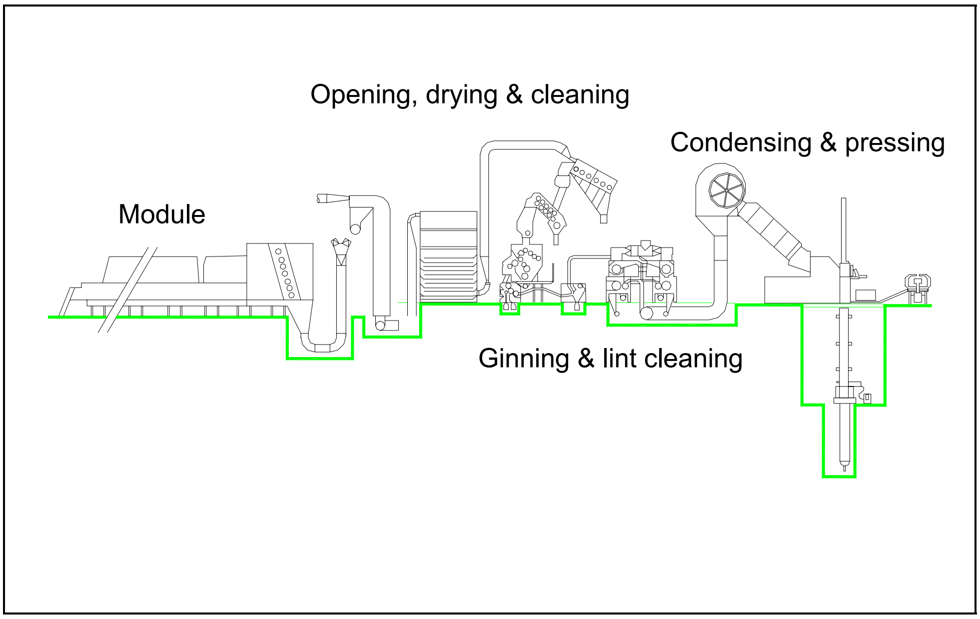


Figure 13 – Cross-section of modern Australian gin

The optimum moisture regain for cotton in the gin varies for each process in ginning and the recommendations for each process also vary in the literature. However, the rule of thumb has been that cotton moisture regain in the 6% to 7% range is best for seed-cotton cleaning, ginning, and lint cleaning to preserve fibre quality, and between 6% to 8% moisture range for ease of press operation and long-term bale storage[85].

As the moisture content of lint decreases, the processing performance of cotton cleaning equipment improves [68 86 87 88 89 90 91]. Ginning at lower moisture contents also result in improved colour[92]. However, ginning at higher moisture contents improves fibre properties by increasing fibre strength, uniformity, and length and reducing short fibre content (SFC)[93 94 95 96]. Other aspects of gin processing are also affected by fibre moisture. The compression force required to bale ginned lint, as well as the bale tie forces, decrease with increasing fibre moisture[97]. Griffin and Merkel[68] also reported that as the fibre moisture increases, the ginning time decreases.

The adverse effects of decreasing moisture content in ginning are related to reduced fibre strength and increased fibre breakage. Moore and Griffin[98] presented data showing that single fibre breaking force increases with increasing moisture content in the range of 3 to 15%, while fibre-seed attachment forces remain constant from 3% to about 11% and then decrease up to 15% moisture content. They also documented that, as seed-cotton was dried from 10% to 4% during the ginning process, trash was removed more efficiently, cotton grades improved, and manufacturing waste declined in the textile mill. Anthony and Griffin[99] in trials, found that as fibre moisture increases one percentage point, fibre breakage would decrease 0.5 percentage points.

Australian research[100 101] has shown similar effects on fibre properties as a result of drying and moistening fibre through the gin, in particular through the gin stand and lint cleaner. Table 2 lists the test results from CSIRO trials in 2001 showing the effect of moisture preservation on HVI properties. Figure 14 illustrates the effect post-gin and post-lint cleaner on staple length of increasing moisture regain above the gin stand in more recent trials[102]. The effect of increasing moisture content from 5.5% to 7.5% through the lint cleaner was in excess of 1/32nd inches on the staple length with concomitant improvements in length uniformity (UNI) and SFC. It was also noted that the transport by air caused fibre moisture losses of between 0.5 and 1.0%, between the back of the gin and the second lint cleaner.

Drying Cotton

Whilst it is only seed-cotton that is purposely dried in cotton gin dryers, ginned lint also loses a significant amount of moisture as it is transported by air through the gin and lint cleaners. As air and cotton move through the gin dryer and gin duct work, moisture is vaporized from the cotton and heat is absorbed by the system of ducting, machines and cotton. Prior to recent seasons most of the drying in Australian cotton gins was done using heated air. However, in the recent dry seasons the ambient condition of the air has been dry enough for ginners to achieve the ‘desired’ equilibrium moisture content without the addition of heat, although in most cases the ambient conditions have resulted in cotton that is too dry, and as a result cotton has been damaged during ginning.

Table 2 – The effect of moisture preservation on fibre quality[100]

GIN TREATMENT*		Moist Zero Heat	Dry Zero Heat	Dry High Heat	Ambient Std. Heat	Moist High Heat
Uster HVI 900	HVICC					
UHML	inches	1.17	1.14	1.14	1.12	1.14
UNI	%	84.1	84.2	83.2	82.9	83.3
SFC	%	2.9	2.7	3.2	5.6	4.7
STR	gf/tex	31.8	30.8	33.9	28.6	31.2
ELO	%	12.7	13	13.1	11.8	13.1

*Dry Storage = 5% moisture pre gin stand, Ambient Storage (module yard) = 7.5% moisture pre gin stand, Moist Storage = 9.5% moisture pre gin stand, Zero Heat = Ambient temperature 25°C – burners off, Standard Heat = Standard temperature 55°C, High Heat = Maximum temperature 90°C – burners on high

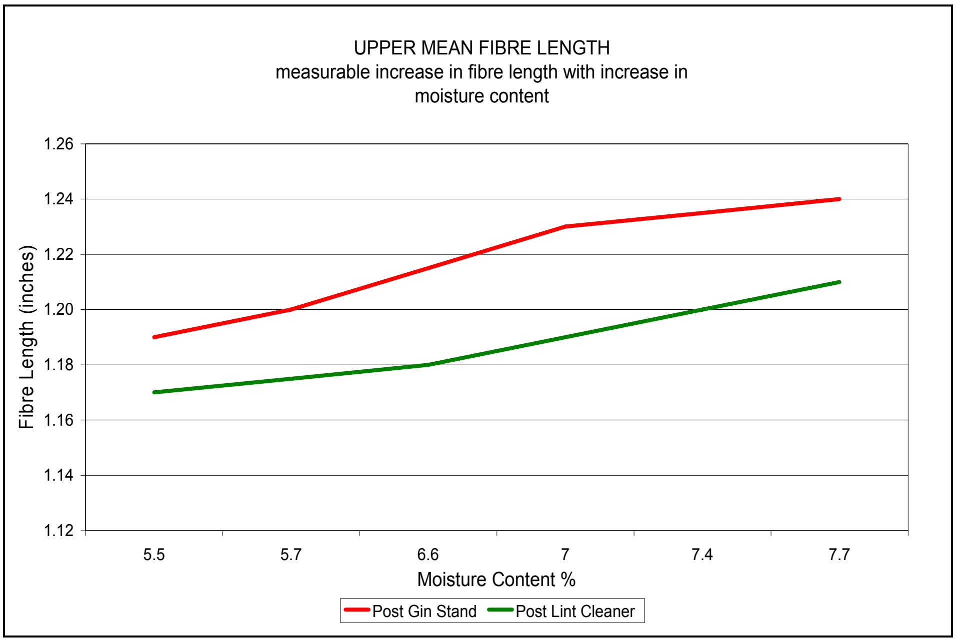


Figure 14 – The effect of moisture addition on fibre length post-gin stand and post-lint cleaner[101]

According to Anthony[102]; drying cotton at high temperatures may damage cotton fibre and should therefore be dried at the lowest temperature to produce satisfactory market grades and allow satisfactory gin operation. In no case should the temperature in any portion of the drying system exceed 177°C because irreversible damage may occur. Temperatures over 121°C cause moderate fibre damage and should not be used if at all possible. Cotton will scorch at 232°C, ignite at 460°C, and flash at 316°C. Anthony and Griffin[99] found temperatures over 93°C damaged dry fibre and should not be used if at all possible. Similarly CSIRO research[100] found that temperatures around 90°C caused significant damage in terms of fibre length and neps compared with cotton dried at 55°C and ambient conditions of around 25°C.

Cotton with too low a moisture content may stick to metal surfaces as a result of static electricity generated on the fibres and cause machinery to choke and stop. Fibre dried to very low moisture content becomes brittle and will be damaged by the mechanical processes required for cleaning and ginning. When a second drying system is used to process high moisture cotton it should be at lower temperatures than the first drying system, as the major moisture removal should be done in the first system. The primary function of the second drying system is to extend the drying time and to keep the seed cotton and the machinery hot and prevent condensation of moisture. Dryers should be adjusted to supply gin stands with lint having a moisture content of 6% to 7%. Cotton at this moisture level is more able to withstand the stresses of ginning without breaking. However, as stated already, cotton with a moisture content of 5% will result in better cleaning and a smoother appearance, which is erroneously preferred by many classing and marketing systems.

Almost all of the moisture removed during the short drying time in commercial gin dryers comes from the fibres rather than from seed and trash. Whilst the seed constitutes 55% to 60% of the weight of spindle-harvested seed cotton its moisture content is considerably less important from a ginning standpoint than the moisture content of the fibres, unless the seeds are so wet that they are soft.

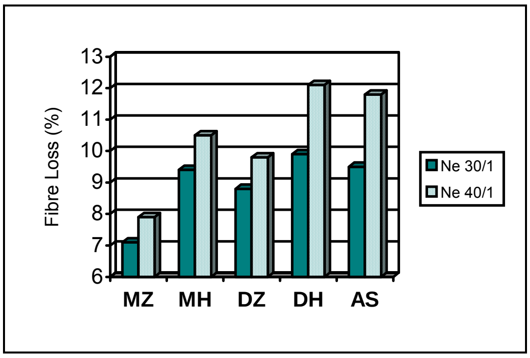
A retrospective view of cotton gin dryers by Mangialardi and Anthony[103] provides a comprehensive review of cotton gin dryers used since the 1920s through to 1996. Automatic systems able to correct heat inputs to affect the moisture of incoming seed-cotton were first researched in the early 1960s[104] and although now available, are not widely used in Australia. These automated drying systems measure seed-cotton moisture; the volume of seed-cotton entering the gin; and then manage bypass valves and/or heat inputs (usually by empirical calculation of the heat required to change moisture content) to realize a prescribed moisture content in the cotton, and to reduce energy, usually gas, inputs. The capability to rapidly monitor two variables; i.e. seed-cotton moisture and volume, crucial to real-time maintenance of an optimal ratio of heat input is relatively recent and not without issues, which centre around the accuracy of the seed-cotton moisture and volume flow measurements. Many gins use non-automated control by staging dry modules to be ginned consecutively and shutting off gas burners altogether when not needed.

An example of a commercially available automatic drying system is the 'IntelliGin' system marketed by Uster Technologies, which uses one or more electrical resistance sensors to measure the moisture content of seed-cotton and lint, and enable control of heat inputs into the system. The Samuel Jackson Inc. 'Moisture Mirror II' system[105] monitors moisture using electrical resistance and VOMAX microwave sensors and provides the operator with instant readings of incoming moisture, post-drying moisture and bale moisture. Using standard cotton flow into gin and ginning rates, the system allows operators instant and/or automatic control of Samuel Jackson 'Humidaire' and dryers. The system is able to let the ginner set the after-drying moisture as a control system target and is able to compensate for sudden upward spikes in the module moisture level. Other systems like the Cliff Granberry Corporation[106], Honeywell[107] and Schaffner[108] moisture sensor systems are less sophisticated with respect to gin control and centre on measuring moisture content, with simple bespoke automated or manual gin control.

Already noted is the damage that occurs to cotton when it is exposed to high temperatures in excess of 90°C. The detrimental effects of high temperatures are amplified at lower moisture contents. Anthony[109] reported that fibre length was reduced from 1 5/32nd to 1 3/32nd inches when moisture was reduced under heat from 7.4% to 3.4% across a number of gin cleaning sequences. Likewise Anthony and Griffin[97] reported SFC increased from 4.6% to 8.7% when moisture at ginning decreased from 8.4% to 4.1%. At the same time, the number of seedcoat fragments increased from 78 to 121 per 3 grams of lint.

Moisture Restoration

To ameliorate the harsh effect of heat and/or dry cotton in the gin, moisture restoration systems are available. These systems typically add moisture to seed-cotton immediately before ginning and in doing so help maintain fibre length and reduce the number of fibres broken at the gin stand and lint cleaners. Childers and Baker[110] used five moisture treatments involving drying and moisture restoration before the gin stand on stripper-harvested cotton. The treatments with no moisture restoration had lint moisture contents of 3% to 5% and the treatments with moisture restoration had a lint moisture content of 5% to 6%. Whilst the treatments did not result in significantly different mean fibre lengths, there were differences in the average yarn break factor with lower yarn breakage correlating with lower fibre moisture content. They concluded that moisture restoration before ginning tended to offset most of the harmful effects of drying on fibre quality. More recent studies by CSIRO[100] confirm positive effects of moisture on fibre (see Table I) and yarn quality. Figure 15 shows the effect of moisture and gin drying temperature on fibre loss during Murata Vortex spinning and yarn evenness, both parameters being affected by increased SFC as a result of dry module storage and heating during ginning. Other benefits resulting from moisture restoration include reducing the static electricity level of the cotton, reducing the volume of the cotton required to achieve a given bale size and reducing the force required to press the bale. The resilient forces exerted on the restraining bale ties are also lower for the higher moisture cotton.



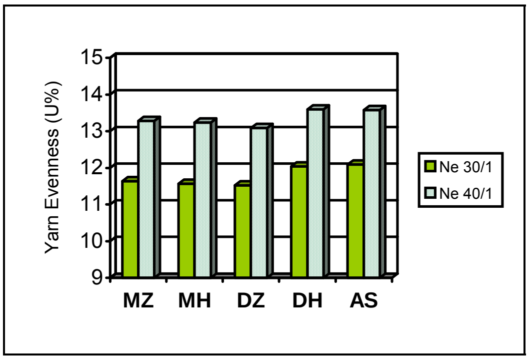


Figure 15 – Effects of dry and moist module storage and cotton dryer temperature on spinning and yarn quality; MZ = moist storage with zero heat, MH = moist storage with high heat, DZ = dry storage with zero heat, DH = dry storage with high heat, AS = ambient storage (dry) and standard heat[100].

Many approaches have been used to restore moisture in cotton fibre. Moisture restoration may occur at several locations such as module feeder, feed control, pre- and post-gin dryer, above extractor feeders, into moving-bed conditioners, at battery condensers and other apparatus in the lint slide[111]. There is a practical physical limit to the quantity of moisture that may be added to seed-cotton. Wetting of the cotton by condensation within machinery and pipes must be prevented or choking will result. If liquid water is present on the seed-cotton mass, gin stand operation will become irregular and may cease altogether. Cotton with fibre moisture in excess of 9% may be rough in appearance and will not smooth out properly when processed through the lint cleaners. Thus, the recommended fibre moisture level of 6% to 7% is based on production aspects as well as quality aspects. Lint moisture in the bale must be uniform and must not exceed 7.5% in order to avoid fibre discoloration and significant weight loss during storage.

One approach is to use humid air to moisten cotton. The air must be heated to carry sufficient moisture to the cotton fibre. Air can carry ten times as much water vapour at 54°C as it can at 16°C – see Figure 16. Humidified air systems first heat air to high temperatures whereby it is then exposed to atomised water droplets, which evaporate into the air. The evaporation process lowers the air temperature and increases the 'dew point' temperature of the air. The dew point temperature of the air must be well above the temperature of the cotton. This humid air is then blown through the cotton, which lowers the air temperature below its dew point causing fine water droplets to form on the cotton fibres throughout the cotton batt. The amount of moisture restoration with this system is limited, especially at higher ginning rates. The Samuel Jackson Humidaire system[105] where humid air is blown into the extractor feeder adds no more than 1.5% and typically no more than 1% moisture to seed-cotton depending on ambient conditions. Whilst in absolute terms this amount seems insignificant, significant improvements are seen in fibre quality (see Figure 14), gin productivity and bale weight as a result.

Another approach is to atomise water and spray it directly on the cotton. Sometimes a wetting agent is added to the water to hasten its distribution through the cotton. Most Australian gins use this type of spray system on the cotton at the lint slide in order to restore moisture and weight to the bale, although sprays can also be applied in other parts of the gin, e.g. in the post-dryer, pre-cleaning area. Extreme care must be exercised to avoid wet spots in the bale, which promote bacterial and fungal growth and cause degradation of the fibre. The addition of moisture to the bale is reviewed in the next section.

A recent study conducted by Byler[112] investigated the effect of installing commercially available atomising nozzles in a commercial cotton gin to apply water to seed-cotton between pre-cleaning and the conveyer-distributor before ginning. The moisture content of lint samples collected between the gin stand and the first lint cleaner was increased by between 0.2% and 1.1% points with this system. Lint subject to the moisture sprays had longer mean length and upper quartile length, and lower SFC. Non-lint content was also higher and nep content lower. Studies by CSIRO[113] in which water and lubricants have been applied by nozzles pre-gin have shown similar results to those of Byler. Atomising sprays must either be applied in line and in the middle of the air (cotton) flow and preferably just prior to a working roller to ensure the spray is applied as evenly as possible to the fibre, and to avoid the building of wet tags in the duct work. Add-on rates in excess of 1% on weight of the fibre (owf) under ambient ginning conditions should be avoided. Higher addons can be applied with increased duct temperature according to Figure 16, although air and duct temperature must be maintained to avoid condensation.

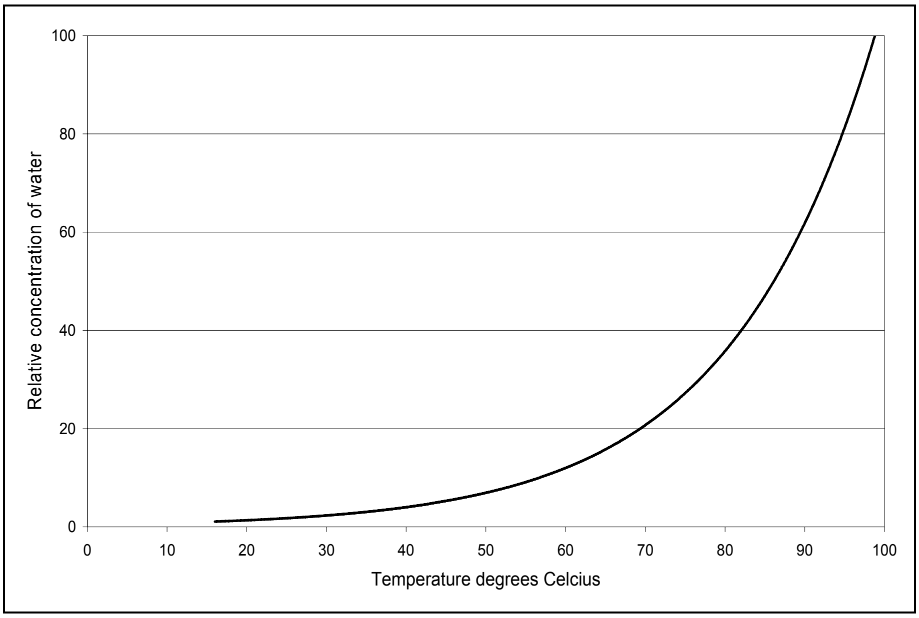


Figure 16 – Relative concentration of water in air with temperature

Moisture in the Bale

During 2003 and 2004 bales pressed with moisture levels in excess of 8% and delivered to overseas spinning mills raised concerns amongst the export segment of the US cotton industry about the addition of water at some US gins. The concerns were based around the degradation of fibre quality in cotton stored at high moisture levels. These incidents and the industry concern that followed led to the National Cotton Council (NCC) Quality Task Force to set forth the following recommendation with respect to moisture in baled lint:

"As precaution against undue risk of fiber degradation and until definitive research data can support higher levels of moisture addition at the cotton gin, the National Cotton Council recommends that moisture levels of cotton bales at the gin not exceed the targeted level of approximately 7.5%."[114]

In late 2006 the USDA issued new provisions (legislation) for cotton bales entering the Cotton Marketing Assistance Loan Program aimed at solving the "wet cotton" problem[115]. The new regulations, which deal with the storage, handling and ginning requirement for cotton pledged as collateral for marketing assistance loans, define *"wet cotton" as a bale that exceeds 7.5% (wet basis) at any point in the bale when measured at the gin*. According to the USDA, bales may not surpass this 7.5% moisture level and be eligible for a marketing assistance loan, according to the regulations, which were part of a final rule issued by USDA in August 2006. The rule also established other new criteria for cotton gins and warehouses.

In February 2007 at the NCC Annual Meeting the Research and Education Committee clarified the NCC's position on acceptable moisture content in cotton lint bales. The following policy recommendations were adopted[116]: That the US cotton industry:

- Continue their reviews of literature and research to determine appropriate moisture levels in baled lint;
- Communicate that information to the cotton industry, and encourage continued research, particularly on a regional basis (recognizing that widely divergent climatic conditions exist throughout the US cotton belt), to determine optimum moisture levels in baled lint that will preserve fibre qualities and spinning performance and mitigate gin bale weight losses;
- As a precaution against undue risk of fibre degradation, recommend that restored moisture levels of cotton bales at the gin not exceed 7.5 % (wet basis);

- Accept the designation of "wet cotton" as defined by USDA as one of the criteria for CCC loan eligibility; and,
- As a requirement for CCC loan eligibility, recommends CCC require gins to disclose on a revised Form 809 the type of moisture restoration system(s) available for use at the gin and that such disclosure be made publicly available.

Prior to 2002 cotton packaging and storage condition research investigations mentioned little about bale moisture levels with respect to long-term storage[85 117]. However, around and after 2003 a spate of investigations describing the effects of high bale moisture levels over time on cotton fibre quality were published[40 118 119 120 121 122 123 124 125 126 127 128]. The general gist of these is that excessive moisture in bales stored for extended periods creates quality problems for merchants and mills. The studies showed moisture augmentation of cotton bales with excessive amounts of water, mainly via spray systems, leads to a reduction in fibre quality. Noted in the studies was that water sprayed on cotton fibre can adversely impact greyness and yellowness, and thus colour grade, at moisture levels as low as 7.3% (measured on a wet basis). The difficulties of applying uniform moisture via sprays to cotton at the battery condenser and lint slide have also been described[129]. Two important problems associated with spray systems are posed: Applying just the right amount of water to reach the most desirable moisture content and; applying the water in an even and consistent manner. The direct spraying of liquid water on the top of a fast moving several inch-thick-batt of cotton, achieves only a uniform application to the top surface of the batt of cotton. It is generally believed that transfer of the liquid water to the remaining 4 to 12 inches of cotton is difficult because raw cotton fibre does not readily absorb liquid water by dint of its hydrophobic wax layer and that the cotton bale is immediately packaged at high densities, which greatly retards any further movement of water vapour or liquid. In this respect humidified air[130], which contains water in a vapour phase is more readily absorbed by fibre, and that it is pulled or blown through the cotton, means that moisture is absorbed in a relatively more uniform manner.

In the most recent review of the effects of moisture sprayed on fibre Chun[128] reported that where excessive moisture was used; up to as high as 15%, fibre quality results indicated that after 116 days of storage bales were more yellow and darker as moisture content increased. Results from another study, where cotton was stored for 6 months and the target moisture ranged from ambient moisture, nominally around 5% to 6%, to 12%, and the moisture content was found to be unevenly distributed in a bale, there were still direct relationships between moisture content and decreased reflectance and increased yellowness of fibre over time. Increased fungal density with increased moisture content was also observed. When lower maximum target moisture ranges were studied; where final moisture content after storage did not exceed about 7.5% moisture, the effect on fibre quality and microbial activity was minimal. This result in particular supports the NCC Quality Task Force recommendation that baled lint not exceed 7.5%.

Other Reasons for Adding Moisture to Bales

Aside from adding weight to dry cotton in order to improve gin turn-out and financial returns, the addition of moisture by ginners is also used to aid the pressing and baling of low-moisture cotton, which is often difficult to press to the desired density. Dry cotton requires more force and power to compress than does moist cotton so when pressing and baling low-moisture cotton, it is often difficult to achieve the desired bale weight and density without adding moisture. Bale tie forces are also strongly influenced by the moisture content of the bale[131] [132]. Tie forces increase over time after compression and release. They also respond to the initial moisture content after packaging[133]. An investigation of bale tie forces over a 130 day storage period showed that tie forces increased for the first 60 days after packaging as the internal moistures of the bales increased and the bales equilibrated to the ambient conditions. Forces then remained constant and bale weight change stabilized at about the same time.

Conclusions & Recommendations

The level of moisture in seed-cotton at harvest through to lint in the bale can have significant effects on the quality of fibre sold to the spinning mill. There are optimum moisture levels for seed-cotton and lint for each harvest and ginning process that allow good and efficient harvesting, cleaning, ginning, baling and safe storage. This report reviews current information on the cotton cellulose moisture complex, the methods applied to, and the processes governed by, measurements of moisture in seed-cotton and fibre, and the potential of systems to accurately and automatically manage moisture during the ginning process. Where possible, the Australian experience with respect to moisture in cotton and ginning is given to bring relevance to the report.

The majority of information about moisture measurement, drying and moisture replenishment, and management comes from US research or manufacturers, which whilst largely relevant is not all applicable to the Australian situation. Notably, most Australian cotton is grown under hot, dry conditions using irrigated water, which delivers yield and quality premiums not seen anywhere else in the world. Australian cotton is cleaner, whiter and, in general, is longer than the bulk of the growths with which it competes. That Australian cotton is cleaner and typically longer demands the question about the relevance of US ginning processes and machines to Australian fibre quality.

Thus the key areas for review, consideration and investigation in terms of cotton moisture and the Australian ginning industry are:

- ***The setting of consistent industry approaches to moisture measurement, and moisture instrument calibration and validation, to ensure industry application of defined levels of moisture during ginning, lint cleaning and baling. It is important that bale moisture is properly managed as bales pressed with more than 7.5% moisture will degrade in quality, particularly over extended storage periods. Moisture levels at the bale press should be recorded and archived for each bale.***

- ***A greater understanding of the moisture equilibrium in cotton under gin conditions particularly with respect to conditions around the Tg of cotton, i.e. the temperature and moisture content at which cotton cellulose changes from a brittle material to one that is more rubber-like and resilient. There are now indications that observing conditions leading to a Tg of cotton would allow fibre properties to be more accurately and concisely set during ginning and pressing.***

- ***The development and then application of more accurate moisture sensing technologies to ginning, particularly during the pre-gin and pre-lint cleaner processes, would enable better control and improved fibre quality to be delivered from Australian gins. Australian cotton is known for having high nep and SFC[134], largely as a result of once-over harvesting and productive ginning systems. Moisture protects fibres from damage during the ginning process. Many studies both here and the USA have shown the beneficial affects of moisture during ginning and lint cleaning. One shortcoming in the process of adding or retaining moisture during ginning is the lack of an accurate and robust moisture sensor that can be incorporated into automated control systems. An accurate sensor would allow the development of monitoring and dosing technologies into systems that control seed-cotton and fibre moisture through the gin with more accuracy.***

- ***The loss of moisture during ginning is largely a result of the large volumes of usually dry, and sometimes hot air, used to transport cotton through ducts between ginning machines The investigation of methods of moving cotton lint within the gin without air and therefore without the associated drying, would be advantageous.***

Table A – Commercial Thermal (Gravimetric) Based Moisture Analysers

Model	Manufacturer	Heat Source	Advan/Disadvan
HR83 Halogen Moisture Analyzer	Mettler Toledo International Inc http://au.mt.com	Circular halogen lamp and gold-plated reflector	For use in regulated environments. With a readability of 0.001% moisture content,
Moisture Tester MT-C	C.W. Brabender Instruments Inc.South Hackensack NJ http://www.cwbrabender.com/	Drying chamber with moving air	Avoids time-consuming cooling of samples in a desiccator by direct measurement after drying
Radwag Moisture Analyzer	Zaklad Mechaniki Precyzyjnej RADWAG Poland http://www.radwag.pl/english/1e_wps1.htm	Consists of two parts: precision balance and attached to it drying chamber equipped with two halogen lamps	Range of capacities of analyzers WPS S is: 50 g /to 0.1 mg, 110 g /to 1 mg, 210 g /to 1 mg. Measuring accuracy for moisture in version 110 and 210 g equals 0.01%. Moisture analyzer with capacity 50 g performs measuring with accuracy of 0.001%

Table B - Commercial Portable and Laboratory Resistance-Based Moisture Meters

Model	Manufacturer	Applications	Advan/Disadvan.
Delmhorst Meters C-2000 with 30-E/C electrode Hand-held	Delmhorst Instrument Co. http://www.delmhorst.com/products_cotton.html	Loose and densely packed lint and seed-cotton	Delmhorst model found to be the best in a paper presented by USDA on 3 meters (Delmhorst, Aqua-Boy and Strandberg models) Sold and recommended by Samuel Jackson Portable hand-held with range of probes for different materials
Strandberg Meters M-200C Analog M-400 Digital Hand-held	Strandberg Engineering Laboratories, Inc. http://www.strandberg.com/	Loose and densely packed lint and seed-cotton	Strandberg offers moisture calibration services for ISO-9000 certification. The M-400 has one simple calibration setting to convert from the standard cotton scaling to other fibres, blends and materials.
Aqua-Boy Meters BAF1 Hand-held	Enercorp Instruments, Ltd., & KPM Moisture Meters http://www.aquaboy.com/Cotton_Moisture_Meters.html	Loose and densely packed lint and seed-cotton	
Chinese Meter Y412B Bench-top		Loose lint and seed-cotton	Less than 50% of samples agreeing within ±0.3% moisture of the reference method
Granberry WR7500 Hand-held	Cliff Granberry Corporation http://www.cliffgranberrycorp.com/	Loose lint and seed-cotton	Accuracy within 0.5% and 1% moisture

Table C – Microwave/Radio-wave Moisture Meters for the Bale

Model	Manufacturer	Applications	Advan/Disadvant
VOMAX 851	VOMAX P/L South Australia http://www.vomax.com.au/	Module and bale Laboratory instrument (VOMAX 465) available for small samples; 25 g of lint or 30 g of seed cotton	Scanning-type sensor that takes thousands of measurements and then displays the average of those readings. Precision claimed to be better than 0.25% (lint) and 0.5% (seed-cototn). Recommended and sold by Samuel Jackson Inc.
MALCAM MMA2020 (online) and MMC2000 (offline)	MALCAM is based in Israel but also has a subsidiary, MALCAM Inc., located in the USA http://www.malcam.com	Bale	Malcam's moisture and density deviation measurement measure the entire volume of the material (like VOMAX).
'Liquidtroller'	Advanced Moisture Technologies (AMT) http://www.advancedsensingandcontrols.com/	Module and bale	Part of a gin control unit uses low frequency microwaves to measure propagation (transmission) delay for microwaves to travel through bale and moisture contained therein. Available as single unit or as sensor in automated gin-control system.

Table D – Commercial Moisture Control Systems

Model	Manufacturer	Sensor	Advan/Disadvant
'Intelligin'	Uster Technologies http://www.uster.com	Resistance	Monitors the ginning process through various sampling stations. Includes a new automated moisture restoration option at bale slide.
Drycom	Streat Instruments http://www.streatsahead.com/	Resistance	Online application available but not standard in gins. Available as laboratory instrument also.
'Process Watch' uses Schaffner sensors the 'IsoTester' and 'GinWizard'	Lubbock Electric Company (LECO) http://www.lubbockelectric.com/	Resistance	In strategic partnership with Schaffner Technologies Inc. Schaffner sensors provide fibre property measures post-bale press with running economic impact to the producer in terms of grade and turn-out. LECO automate gin set-ups according to recommend changes by Schaffner sensors.
'Moisture Wizard' (new)	Schaffner Technologies http://www.schaffnertech.com/	Resistance	Newly listed on Schaffner website as moisture measurement and control tool. No details published.
'Moisture Mirror'	Samuel Jackson Inc. http://samjackson.net/	Resistance and microwave (VOMAX)	Four different 'Moisture Mirror' models each utilising a number of different moisture measurement sensors. Integrated automation of drying and replenishment.

References

[1] Goldthwaith, F. G. and Guthrie, J. D., (1954), *Matthew's Textile Fibers*, H. R. Mauersberger (ed.), Wiley Interscience, New York

[2] Jefferies, R., Jones, D. M., Roberts, J. G., Selby, K., Simmens, S. C. and Warwicker, J. O., (1969), Current ideas on the structure of of cotton, *Cellulose Chem Technol*, **3**, 255-274

[3] French, A. D., (1985), Physical and theoretical methods for determining the supramolecular structure of cellulose, in *Cellulose Chemistry and its Applications*, Nevell, T. P. and Zeronian, S. H. (eds.), Chichester, Ellis Horwood Ltd.

[4] Meredith, R., (1953), Properties depending on the amorphous regions of fibres, *Fibre Science*, 2nd edition, Preston, J. M. (ed.), The Textile Institute , Manchester, 236-262

[5] Pierce, F. T., (1929), A two-phase theory of the absorption of water vapour by cellulose, *J. Textile Inst.*, **20**, T133-150

[6] Barkas, W. W., (1949), *The swelling of wood under stress*, London, HMSO

[7] French, A. D., Goynes, W. R., Rousselle, M. A. and Thibodeaux, D. P., (2004), Cotton fiber and moisture some of the basics, *Proceedings of the Beltwide Cotton Conferences*, San Antonio TX

[8] Hearle, J. W. S., (2007), Physical structure and properties of cotton, in *Cotton: Science and Technology*, Gordon, S. G. and Hsieh, Y. L. (eds.), Woodhead Pub., Cambridge, 35-67

[9] Perel, J., (1990), An x-ray study of regain-dependent deformation in cotton crystallites, *J. Textile Inst.*, **81**, 241-244

[10] Taylor, R. A. and Godbey, L. C., (1993), A reference method for HVI strength, *Proceed. Beltwide Cotton Conf.*, New Orleans LA, National Cotton Council, 1076-1079

[11] Meredith, R., (1946), Molecular orientation and the tensile properties of cotton fibres, *J. Textile Inst.*, **37**, T205-T218

[12] Jawson, M. A., Giles, P. P. and Mark, R. E., (1968), The elastic constants of crystalline native cellulose, *Proceedings Royal Soc.*, **A306**, 389-412

[13] Taylor, R. A., (1990), Moisture analysis for HVI testing of cotton, *Textile Res. J.*, **60**, 94-102

[14] Fox, T.G., (1956), Influence of diluent and of copolymer composition on the glass temperature of a polymer system, *Bull. Am. Phys. Soc.*, **1**, 123

[15] Wortmann, F. J., Rigby, B. J. and Phillips, D. G., (1984), Glass transition temperature of wool as a function of regain, *Textile Res. J.*, **54**, 6-8

[16] Rippon, J., (2003), Wool, in *Encyclopedia of Polymer Science and Technology*, Interscience Publishers, New York

[17] Maxwell, J. M., Gordon, S. G., Huson, M. G., (2003), Internal structure of mature and immature cotton fibers revealed by scanning probe microscopy, *Textile Res. J.*, **73**, 1005-1012

[18] Phillips, D. A., (2006), Unpublished work, CSIRO Textile and Fibre Technology

[19] **(1975), *Polymer Handbook*, 2nd Edition, J. Wiley & Sons, New York**

[20] Henry, P. S. H., (1939), Cotton bales: Uptake of water, *Proceedings Roy. Soc.*, **A171**, 215-241

[21] Morton, W. E. and Hearle, J. W. S., (1993), *Physical properties of textile fibres*, The Textile Institute, Manchester

[22] Anthony, W. S., (1982), Effect of bale covering and density on moisture gain of cotton bales, *The Cotton Ginners Journal and Yearbook*, **50**, 7-18

[23] Anthony, W. S., (1997), Solving gin-related cotton bale tie failures, *The Cotton Gin and Oil Mill Press*, **98(24)**, 5-11

[24] Anthony, W. S., (2003), Impact of excess moisture in the bale on fiber quality, *Proceedings of the Beltwide Cototn Conferences*, Nashville TN

[25] Anthony, W. S., (2003), Impact of excess moisture on cotton bales stored in polypropylene bagging, *The Cotton Gin and Oil Mill Press*, **104(25)**, 5-10

[26] ASTM Standard D1909, (2004), Table of commercial moisture regains for textile fibres

[27] Australian Oilseeds Federation, Commercial Standards, (2004), Issue No. 1, 16 pp

[28] Cabrera,E. R., and Mourad, H. A., (1995), Cottonseed moisture determination, *Seed Sci. & Technology*, **23**, 629-638

[29] Hart, J. R. and Golumbic, C., (1963), Methods of moisture determination in seeds, *Proceedings of the International Seed testing Association*, **28**, 911-933

[30] Fischer, K., (1935), Neues Verfahren zur ma Banalytischen Bestimmung des Wassergehaltes von Flussigkeiten und festen Korpern, *Angew. Chem.*, **48**, 394-396

[31] Smith, D. M. and Bryant, W. M. D., (1935), Titrimetric determination of water in organic liquids using acetyl chloride and pyridine, *J.Amer.Chem.Soc.*, **57**, 841-845

[32] Montalvo, J. G. and von Hoven, T., (2004), Analysis of cotton, American Society of Agronomy, Crop Science Society of America, Soil Science Society of America (pubs.), in *Near-Infrared Spectroscopy in Agriculture*, Agronomy Monograph no. 44, 671-728

[33] Anthony, W. S., (1991), Field evaluation of infrared moisture meters, *Appl. Engineering in Agriculture*, **7**, 509-514

[34] Thomasson, J. A., (1995), Cotton moisture measurement with a black and white video camera, *Applied Engineering in Agriculture*, **11**, ASAE, 371-375

[35] Hearle, J. W. S., (1953), The electrical resistance of textile materials. Part I. The influence of moisture content, *J. Textile Inst.*, **44**, T117-143

[36] van der Sluijs, M. H. M., (2007), Initial BMP audit of Australian gins, Report to the Australian Cotton Research and Developement Corporation, 50 pp

[37] Byler, R. K., (2007), Personal communication

[38] Byler, R. K., Baker, K. D., Hughs, S. E., Pelletier, M. G., Holt, G. A., Buser, M. D., and Carroll, J. A., (2006), Examination of some currently available portable cotton bale moisture meters, *Proceedings of the Beltwide Cotton Conferences*, San Antonio TX

[39] Pelletier, M. G., (2006), Absolute moisturesensing for cotton bales, *Proceedings of the Beltwide Cotton Conferences*, San Antonio TX

[40] Valco, T. D., Anthony, S. W., Byler, R. Pelletier, M., Hughs, S. Ed. And Norman, B. M., (2004), Moisture restoration of cotton, *The Cotton Gin and Oil Mill Press*, September, 5-8

[41] Byler, R. K., (2004), A device for rapidly predicting cotton lint moisture content, *Transactions of the ASAE*, **47(4)**,1331-1335

[42] Byler, R. K., (2006), Resistance-type portable cotton lint moisture meter, *Appl. Engineering in Agriculture*, **22**, 13-17

[43] http://www.uster.com/

[44] Byler, R. K. and Anthony, W. S. , (1996), System for analyzing moisture content of materials such as cotton, US Patent Number 5,514,973, 12 pp

[45] Breazeale, W. Mc., (1953), Method and apparatus for measuring moisture content, US Patent No. 2659860, 7 pp

[46] Greenwald, A., Nazareth, I., Moshe, D. S., Kiryat, O. and Tsentsiper, B., (1997), Device and method for determining the moisture content of a bale of material with multiple layers, US Patent No. 5621330, 13 pp

[47] Pelletier, M.G., (2004), Multi-path interference investigation for cotton bale microwave moisture sensing, *J. Cotton Sci.*, **8**, 170-178

[48] Pelletier, M.G., (2005), Multi-path interference mitigation for cotton bale microwave moisture sensing, *J. Cotton Sci.*, **9**, 135-144

[49] Kelly, R. K. and Kuchar, K. M., (2001), Method and means for moisture measurement, US Patent No. 6278412, 13 pp

[50] Pelletier, M.G., (2007), Microwave moisture sensing of wet bales, *Proceedings of the Beltwide Cotton Conferences*, New Orleans LA

[51] Irick, G. E., Gaylon, M. E. and Ghorashi, H., (2005), Ultra low frequency moisture sensor, US Patent No. XYZ

[52] Kelly, R. K., (2007), Personal communication

[53] Anthony, W. S. and McCaskill, O. L., (1976), Determination of the compressive characteristics of lint cotton with a model bale press, *USDA Technical Bulletin No. 1546*

[54] Anthony, W. S., (1998), Development of a method to estimate the moisture of cotton bales, *Proceedings of the Beltwide Cotton Conferences*, Memphis TN, 1641-1643

[55] Byler, R. K. and Anthony, W. S., (2003), Measurement of bale moisture content based on bale compression pressure, *Proceedings of the Beltwide Cotton Conferences*, Nashville TN

[56] Gillum M. N. and Armijo C. B., (1997), Modeling seed cotton moisture from air temperature drop and mass flows, *Proceedings of the Beltwide Cotton Production Conference*, 563-567

[57] ASTM Standard D2495, (2007), Method for measuring moisture in cotton by oven-drying

[58] Phair, N. L., (2002), Unpublished data

[59] Reichmuth, A., Wunderli, S., Weber, M. And Meyer, V. R., (2004), The uncertainty of weighing data obtained with electronic analytical balances, *Microchim. Acta*, **148**, 133-141

[60] International Seed Testing Association, (1993), International rules for seed testing, *Seed Sci. Technology*, **21**, 229-231

[61] ISO Standard 665, (2000), Oilseeds: Determination of moisture and volatile matter content

[62] BS EN ISO Standard 665, (2000) Oilseeds: Determination of moisture and volatile matter content

[63] DIN EN ISO Standard 665, (2002), Oilseeds: Determination of moisture and volatile matter content

[64] MacKay, B. H., (1963), The CSIRO direct reading regain tester, *J. Textile Inst.*, **54**, T376-384
[65] *Cotton Ginners Handbook*, (1994), Anthony, W. S. and Mayfield, W. D. (eds.), USDA ARS Publication No. 503, 337 pp
[66] Mayfield, W., Lalor, W. and Huitink, G., (no date), Harvesting: Spindle pickers and cotton quality, Cotton Incorporated publication, Raleigh NC
[67] Anthony, W. S, (2004), Moisture management practices at gins, *Proceedings Cotton Incorporated Engineered Fiber Selection Conference*, Greenville SC
[68] Griffin, A. C. Jr. and Merkel, C. M., (1953), Moisture content of seed cotton in relation to cleaning and ginning efficiency and lint quality, USDA Production and Marketing Administration, Cotton Branch, US Gov. Print. Office, Washington DC
[69] Sorensen, J. W. Jr. and Wilkes, L. H., (1973), Seed quality and moisture relationships in harvesting and storing seed-cotton, *Proceedings Seed Cotton Storage and Handling Seminar*, Cotton Incorp. (pub.), Phoenix AZ
[70] Curley, R., Roberts, B., Kerby, T., Brooks, C. and Knutson, J., (1990), Effect of moisture on moduled seed-cotton, *Proceedings of the Beltwide Cotton Conferences*, Las Vegas NV
[71] Curley, R., Roberts, B., Kerby, T., Brooks, C. and Knutson, J., (1987), Effect of seed-cotton moisture level and storage time on the quality of lint in stored modules, *Proceedings of the Beltwide Cotton Conferences*, Dallas TX
[72] Anthony, W. S., (1999), Post-harvest management of fiber quality, in *Cotton fibers: Development biology, quality improvement and textile processing*, Basra, A. S. (ed.), Food Products Press, Binghampton NY, 293-333
[73] Williford, J. R., (1992), Influence of harvest factors on cotton yield and quality, *Transactions of the ASAE*, **35**, 1103-1107
[74] Brashears, A. D., Keeling, I. W. and Valco, T. D., (1997), Storage of seed-cotton after four harvest-aid treatments, *Proceedings of the Beltwide Cotton Conferences*, New Orleans LA
[75] Lalor, W. F., Willcutt, M. H. and Curley, R. G., (1994), Seed-cotton storage and handling, in *Cotton Ginners Handbook*, Anthony, W. S. and Mayfield, W. D. (eds.), USDA ARS Publication No. 503, 16-25
[76] Byler, R. K., (2005), Preliminary data on fiber properties of newly harvested versus weathered cotton, *Proceedings of the Beltwide Cotton Conferences*, New Orleans LA
[77] Willcutt, M. H., Hillary, H. and Ruscoe, J., (1995), Evaluation of cotton module tarp material permeability on stored lint color, seed-cotton moisture and temperature, *Proceedings of the Beltwide Cotton Conferences*, San Antonio TX
[78] Parker, R. E. and Wooten O. B., (1964), Sources of moisture in mechanically harvested seed cotton and its effects on cotton quality, USDA ARS Technical Bulletin No. 1313, 25 pp
[79] Anthony, W. S., (2006), The harvesting and ginning of cotton, in *Cotton: Science and technology*, Gordon, S. G. and Hsieh, Y. L. (eds.), Woodhead Publishing, Cambridge, 176-201
[80] Dunlop, G., (2007), Personal communication
[81] Anthony, S. W. and Byler, R. K., (1998), Measurement of moisture content during harvesting and moduling, *Proceedings of the Beltwide Cotton Conferences*, San Diego CA
[82] Byler, R. K. and Anthony, S. W., (1999), Update on an automated in-field cotton lint moisture measurement system, *Proceedings of the Beltwide Cotton Conferences*, Orlando FL
[83] Ag Leader Technology, (2005), Product catalogue
[84] http://www.vomax.com.au/
[85] Anthony, W. S., Van Doorn, D. W. and Herber, D., (1994), Packaging lint cotton, in *Cotton Ginners Handbook*, Anthony, W. S. and Mayfield, W. D. (eds.), USDA ARS Publication No. 503, 119-142
[86] Mangialardi, G. J. Jr., and Griffin, A. C. Jr., (1966), Lint cleaning at cotton gins: Effects of fiber moisture and amount of cleaning on lint quality, ARS Technical Bulletin No. 1359, USDA, Washington DC
[87] Cocke, J. B. and Garner, W. E., (1972), Effect of ginning and spinning efficiency and quality on fiber moisture, seedcotton cleaning, and lint cleaning, ARS Production Research Report No. 143. USDA, Washington, DC
[89] Anthony, W. S., (1983), Response of fiber properties to gin machinery and moisture during ginning as measured by HVI, *J. Eng. Ind.*, **105**, 1-5

[89] Anthony, W. S., (1990), Performance characteristics of cotton gin machinery, *Transactions of the ASAE*, **33**,1089-1098

[91] Anthony, W. S., (1996), Impact of cotton gin machinery sequences on fiber value and quality, *Appl. Eng. Agriculture*, **12**, 351-363
[91] Anthony, W. S., (2002), Influence of cotton varieties and gin machinery on trash particles, *Appl. Eng. Agriculture*, **18**, 183-195
[92] Anthony, W. S., (2004), Impact of adding moisture at the gin lint slide on cotton fiber quality, *Appl. Eng. Agriculture*, **20**, 719-734
[93] Moore, V.P., and A.C. Griffin, Jr. 1964. The relationship of moisture to cotton quality preservation at gins. ARS Report No. 42-105. USDA, Washington, D.C.
[94] Mangialardi, G. J. Jr., Griffin, A. C. Jr., and E.H. Shanklin. 1965. Moisture restoration to cotton at the gin: effects on fiber and spinning properties. ARS Marketing Research Report No. 708. USDA, Washington, D.C.
[95] Leonard, C.G., Ross, J.E., and R.A. Mullikin, Moisture conditioning of seed cotton in ginning as related to fiber quality and spinning performance, ARS/ERS Marketing Research Report No. 859, 1970, USDA, Washington, D.C.
[96] Anthony, W. S. and Griffin, A. C. Jr., (2001), Fiber breakage at gins: Moisture and heat, *The Cotton Gin and Oil Mill Press*, **102(23)**, 10-13, and **102(24)**, 6-9
[97] Anthony, W. S. and McCaskill, O. L., (1973), Forces involved in packaging lint cotton, *The Cotton Gin and Oil Mill Press*, **74(15)**, 7-11,
[98] Moore, V. P. and Griffin, A. C. Jr., (1964), The relationship of moisture to cotton quality preservation at gins, USDA ARS Publication No. 42-105, US Gov. Print. Office, Washington DC
[99] Anthony, W. S. and Griffin, A. C. Jr., (2001), Fiber breakage at cotton gins: Causes and solutions, *Proceedings of the Beltwide Cotton Conference*, Atlanta GA
[100] Gordon, S. G., (2001), The effects of nep and short fibre levels on Murata Vortex Spinning (MVS) efficiency and quality, *The Australian Cotton Grower*
[101] CSIRO-Auscott Moisture Trials, (2007), Unpublished data
[102] Anthony, W. S., Van Dorn, D., Pearson, E., Malloum, T. J., Kechagia, U., Ozdemir, I. and Nyoni D., (2001), Impact of ginning on fiber quality: The best ginning practices, Report of an expert panel on ginning methods, International Cotton Advisory Committee, Washington DC, 27 pp
[103] Mangialardi, G. J. Jr. and Anthony, W. S., (2001), Retrospective view of cotton gin dryers, The Cotton Foundation, Memphis TN, 54 pp
[104] Griffin, A. C. and Mangialardi, G. J. Jr., (1961), Automatic control of seed cotton drying at cotton gins: A review of research, *USDA ARS Report*, Washington DC, 42-57
[105] http://samjackson.net/
[106] http://www.cliffgranberrycorp.com/
[107] http://hpsweb.honeywell.com/
[108] http://www.schaffnertech.com/
[109] Anthony, W. S., (1994), The effect of gin machinery on measurement of high volume instrument color and trash of cotton, *Transactions of the ASAE*, **37(2)**, 373-380
[110] Childers, R. E. and Baker, R. V., (1977), Effect of moisture conditioning on ginning performance and fiber quality of high plains cotton, *Transactions of the ASAE*, **21(2)**, 379-384.
[111] Hughs, S. E., Mangialardi, G. J. Jr. and Jackson, S. G., (1994), Moisture control, in *Cotton Ginners Handbook*, Anthony, W. S. and Mayfield, W. D. (eds.), USDA ARS Publication No. 503, 58-68
[112] Byler, R. K., (2007), Seed cotton moisture restoration in a commercial gin: Initial data, *Proceedings of the Beltwide Cotton Conferences*, New Orleans LA
[113] Gordon, S. G., (2002), Lubricants for improved ginning and spinning of cotton. A fresh approach to length preservation in cotton processing, *Proceedings Beltwide Cotton Conferences*, Atlanta GA
[114] National Cotton Council, (2003), NCC quality task force adopts bale moisture recommendation, News Release, 10th Oct. 2003, National Cotton Council, Memphis TN, *available online at* http://www.cotton.org/tech/quality/upload/05balemoisturemanagementpaper.pdf
[115] US Department of Agriculture Commodity Credit Corporation, (May 2006), 7 CFR Part 1427, Storage, handling and ginning requirements for cotton marketing assistance loan collateral, Federal Register/Proposed Rules, **71:102**, 30318-30323
[116] Smith, R., (Feb 2007), At annual meeting NCC tackles cotton quality issues, http://deltafarmpress.com/mag/
[117] Cable, C. C., Smith, H. R. and Looney, Z. M., (1964), Changes in quality and value of cotton bales and samples during storage, USDA Economic Research Service, AMS Marketing Research Support No 645, 58 pp
[118] Anthony, W. S., (2003), Impact of moisture on baled cotton, *Transactions ASAE Meetings*, Paper No. 031167, 37pp

[119] Anthony, W. S., (2003), The impact of excess moisture in the bale on fiber quality, *Proceedings of the Beltwide Cotton Conferences*, Nashville TN

[120] Chun, T. W. and Anthony, W. S., (2002), Biological degradation of cotton bales due to excess moisture, *Proceedings of the Beltwide Cotton Conferences*, Atlanta GA

[121] Chun, T. W., McAlister, D. and Cobb, D., (2003), Microbial activity of stored cotton bales baled at different moisture levels, *Proceedings of the Beltwide Cotton Conferences*, Nashville TN

[122] Hughs, E., McAlister, D., Armijo, C. and Baker K., (2004), Bale moisture addition-A case study, *Proceedings of the Beltwide Cotton Conferences*, **Memphis TN**

[123] Baker, K. D., Hughs, S. E. and McAlister, D. D., (2005), Bale moisture addition with a rotor spray system, *Proceedings of the Beltwide Cotton Conferences*, New Orleans LA

[124] Chun, T. W. and Anthony, W. S., (2004), Effects of adding moisture at the gin lint slide on cotton bale microbial activity and fiber quality, *J. of Cotton Science*, **8**, 83-90.

[125] Chun, T. W., McAlister, D. D. and Cobb, D. R., (2005), Microbial activity of stored cotton bales with ambient and moderate moisture levels, *J. of Cotton Science*, **9**, 24-29

[126] http://www.ars.usda.gov/Research/Reports/cotton/maxmoistbaledcotton.htm#Recommendation

[127] McAlister, D. D., Hughs, S. E., Chun, T. W., Cobb, D. R. and Backe, E., (2005), Determining an acceptable cotton bale moisture range to avoid fiber quality degradation during long-term storage, A White Paper, at http://www.cottonmoisture.com/files/summary.pdf

[128] Chun, T. W., (2007), Summary of collaborative studies on cotton bale moisture, *Proceedings of the Beltwide Cotton Conference*, New Orleans LA

[129] Mangialardi, G. J. Jr. and Griffin, A. C., (1977), Restoring moisture to cotton at midsouth gins, USDA Tech. Bull. 1553, US Gov. Print. Office, Washington DC

[130] Cory, M. D., (2007), Cirrus cotton conditioner: New methodology for moisture restoration prior to baling, *Proceedings of the Beltwide Cotton Conference*, New Orleans LA

[131] Anthony, W. S., (1982), Analysis of cotton bale tie failures: A user's guide, *The Cotton Gin and Oil Mill Press*, **83**, 14-17

[132] Anthony, W. S., (2000), Forces exerted on cotton bales with six and eight-tie patterns of steel strapping, *Appl. J. ASAE*, **16(1)**, 23-30

[133] Anthony, W. S., (2001), Concept to reduce cotton bale packaging forces, *Appl. J. ASAE*, **17(4)**, 433-440

[134] Gordon, S. G., Van der Sluijs, M. H. J. and Prins, M. W., (2004), Quality Issues for Australian Cotton from the Mill Perspective, Report to Australian Cotton Industry, Australian Cotton CRC (pub), 55 pp