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Potential for Improved Cotton Moisture Measurement

Report to the CRDC, February 1997

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by

Grant Roberts, BEng(Ag)
National Centre for Engineering in Agriculture
University of Southern Queensland
Toowoomba Q, Australia

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EXECUTIVE SUMMARY

This report presents the results of a six month investigation into the need for and feasibility of developing an automatic moisture measuring system for cotton. The report was commissioned by the CRDC in response to a proposal from the NCEA to develop a module-scale moisture scanner using different technology to that in existing equipment.

The investigation established that there is a significant need for reliable instruments to scan seedcotton modules and ginned lint bales and accurately give the moisture content. Such technology is sought in cotton processing applications from picking to baling. Industry personnel agree that the accurate determination of cotton moisture levels would allow increased returns to growers. During processing the scanner would indicate local moisture content within modules and allow the proper setting of burners, reducing overdrying and damage to the fibre. It would also reduce fuel costs to the gins, and provide more confidence when trialing minimum drying and cleaning setups for "gentle ginning".

In another form the same technology could also allow merchants and ginners to accurately check bale weights and provide more rigorous control of moisture content during classing and spinning operations.

The report has been completed in three stages. The problems and issues to do with moisture measurement were first identified (Section 2), the range of technologies available to address those issues was then evaluated (Section 3), and the expert opinions and reactions of ginners and other industry personnel in Australia and the USA were then obtained (Sections 4 & 5).

The studies and discussions confirmed that the proposed moisture measuring scanner would bring considerable benefits to the industry, and may well provide an exportable product. It was also established that gin operators would prefer the initial system to be located on the module feeder rather than on the weighbridge as was originally proposed. They also confirm that the system be developed to allow improved process control in ginning.

It is recommended as follows:

(i) That research be undertaken to develop a module-scale moisture scanner based on the use of ionizing radiation, as outlined in the NCEA research proposals to the Cotton Research and Development Corporation in February 1996 (NCEA 1996) and 1997.

(ii) That, once the measurement system is proven, research should be undertaken to incorporate the technology within the process control of cotton ginning.

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1. OVERVIEW AND INTRODUCTION

The following report details a thorough investigation of Research and Development in the area of measuring moisture in cotton primarily in the cotton gin. This follows a request from the Cotton Research and Development Corporation in their letter of 17th April 1996 to the National Centre for Engineering in Agriculture.

The report sets out a description of the particular problem that lies behind this project from the viewpoint of an engineer concerned with measurement and control. The physical processes that are candidates for a measurement method to solve the problem are described, and a summary of work published in the academic literature concerned with those processes is presented.

The input of interested parties in the Australian cotton ginning and growing industry is presented in the form of a list of issues. Relative to Australian agriculture in general, skill levels in the cotton growing and ginning industry are higher, and people in the industry are more inclined to pool knowledge, to seek "best practice", and to involve themselves in continuous improvement. This occurs in recognition of the fact that the minimum requirements for involvement in the industry are higher than for other lower cost, lower risk, lower return sections of primary industry, and that the penalties for failure are also higher.

A following section presents views from people in the United States industry who were contacted as part of a visit to the USA in October and November, 1996.

The results of a survey of current research work in the area of measuring moisture in cotton, primarily in the United States, are provided.

Recommendations based on knowledge gained during this project are provided at the end of this report.

2. THE PROBLEM - MEASURING MOISTURE CONTENT OF SEEDCOTTON

2.1 Cotton Fibre

Cotton lint is composed of individual fibres comprising an outer primary wall rich in calcium and an inner secondary wall made chiefly of cellulose, a polymer of many individual glucose molecules, making up bundles of hollow fibres as shown in Figure 1.

FIGURE 1 MICROGRAPH OF COTTON FIBRES
(Source: http://nola.srrc.usda.gov/cotton/cotupcl.html)

The primary wall is laid down within the boll at an early stage, and the secondary wall is then laid down as micro-fibrils of cellulosic compounds so that the flat immature fibre becomes a hollow irregular shaped tube with relatively thick walls. Under the influence of stress, chemicals, and natural variations, not all of the fibres will mature properly, and will exist among the fibres as flattened immature fibres with little or no cellulose in the walls.

Being a natural product it is highly variable in length, maturity (manifested as cross-sectional shape and proportion of primary to secondary wall), the statistical distribution of lengths in a sample, wall thickness, fibre thickness, shape, strength and colour. The fibre may be mixed with seed, leaf matter, sticks, dirt, and gross foreign objects into an aggregation of unknown density and proportions. Some of these attributes are fixed or relatively fixed once set, being due to plant variety, soil, weather during critical times, harvesting technique and ginning history. Others vary strongly with time.

2.2 Influence of Moisture Content

A major influence on cotton is its moisture content (USDA-ARS, 1994), (Griffin, 1961). Importantly, cotton lint is sold by weight and this varies strongly with moisture content. In addition, moisture content has a strong effect on the strength of the cotton fibre and its ginning characteristics. Both in its trashy seedcotton module form and when baled as lint, the cotton can suffer from rapid growth of microbiological organisms beyond about 12% moisture which can degrade fibre quality within 24hrs. The quality of the cotton seed also suffers. The heat released by this activity may cause spontaneous combustion which is a serious concern because modules or bales are typically stored in bulk and hundreds of thousands of dollars worth of cotton may be threatened.

2.3 Factors Affecting Moisture Content

The moisture content of cotton varies according to a number of factors, as follows.

2.3.1 Ambient air moisture: Cotton has a relatively high ratio of surface area to mass, and readily exchanges moisture with the surrounding air according to the relative humidity of the air and the air flow between the fibres. The ambient moisture content at an inland gin will often be appreciably different from that at a coastal merchant warehouse.

2.3.2 Equilibration time: If cotton is tightly packed into a bale or a seedcotton module there will be a period of up to 100 days before the entire mass of cotton reaches approximate equilibrium with the surrounding air. Because of this large time constant, the moisture content of the mass of cotton will not exactly match that of the ambient air, and the moisture content at one depth within the mass of cotton will not exactly match that of other depths.

2.3.3 Temperature of cotton: The release of water to the air is aided by the higher temperature of the cotton fibres (distinct from the temperature of the surrounding air).

2.3.4 Time in dryer/transport: (Related to "Temperature of cotton".) Due to moisture content gradients within cotton bolls and seeds, the cotton takes much longer to dry than the residence time within the dryer. This provides buffering for a limited time against overheating when the burner is set too high. This residence time is at speeds dictated by pneumatic conveying (≈25m/s). A longer transport time following the dryer means more drying for same burner setting and dryer equipment, but more power required for transport.

2.3.5 Amount of large leaf trash: If harvested by stripper, or if harvested by either a picker or stripper at too fast a rate, more leaf material in the form of leaf fragments over ≈4mm² in size finds its way into the seedcotton. This material is high in moisture and raises the moisture content of the whole cotton module accordingly. This moisture "sweats" out of the leaf trash over time and manifests itself as an extra variation in the moisture content of the module.

2.3.6 Moisture content of cotton seed: A cotton module with a moisture content of 12% (at the wet end of the acceptable range) may be adequately dried to 5% given enough drying effort in a typical cotton gin. However, if the value of 5% has been determined by reference to the lint still attached to cotton seed (*e.g.* using conductance-based meters) then the average moisture content of the seedcotton is in fact higher. The drying has taken place over a matter of seconds and has really only happened within the lint. The cotton seed is still at close to 12% because of its larger time constant when drying. The hollow cotton fibre acts as a conduit drawing moisture from the seed to itself. Consequently the measured moisture content of the seedcotton varies significantly with time even without more drying effort.

2.3.7 Time of harvesting: If cotton is harvested too early in the morning or too late at night then any dew on the cotton plant is included in the harvested seedcotton. This may raise its moisture content to hazardous levels. During the middle of the day the cotton plant dries out and the moisture content falls markedly.

2.3.8 Rain and flooding: Rain falling on open cotton bolls is absorbed and may then take many days to dry out enough for harvesting to recommence. The significance of this effect depends on whether the bolls tend to face upwards, downwards, or in-between according to the variety of cotton. In addition, storm rain can leave modules standing in centimetres of water making the bottom portion saturated.

2.3.9 Tarping of modules: Modules are tarped against rain because of the possible time delay between harvesting and ginning. Tarps in poor condition or poorly roped down can funnel rain into modules causing 'hot spots' of saturated cotton. These hot spots may travel through a gin faster than the controls can be adjusted and result in bales containing a proportion of poorly cleaned and/or poorly ginned cotton. The whole bale will then be discounted at sale.

2.3.10 Ginning history: The moisture content of seedcotton coming into a gin may vary between 4% and 18%, but cotton bales on leaving a gin are ideally at 8% moisture content measured on a wet weight basis. The actual final value can vary according to the amount of heat put into the cotton prior to ginning, the distance traveled between the point where heat is added and the ginstands, the amount of mechanical work done on the cotton fibre during the cleaning and ginning processes, the flow rate of water added after drying for ginning, the amount of heat added to aid the absorption of water, the distance between the point where water is added and the bale press, and the transport rate of cotton within the gin.

2.4 Summary

In summary, the attributes, behaviour, and value of cotton can be properly described only by reference to its moisture content at the time. However the universal industry experience, both in Australia and the US, is that the moisture content of cotton is not readily measured using current technology. Consequently there are uncertainties in the processing, storage and marketing of cotton. The scale of these uncertainties is not quantified here but is reckoned within the industry to be substantial. These uncertainties could be substantially reduced if a better means of measuring moisture content was available to the industry. "Better" in this context means more precise and accurate, cost effective and practical.

3. REVIEW OF TECHNOLOGY AND ACADEMIC LITERATURE

3.1 Introduction

Moisture content in this report is calculated on percentage wet weight basis, *i.e.* as the weight of water in a sample as a percentage of the wet weight of that sample.

$$MC\% = \frac{M_{DW} - M_D}{M_{DW}} \times 100\%$$

where M_{DW} = Mass of dry material and water
M_D = Mass of dry material alone

Seedcotton is harvested cotton with the cotton fibre still attached to the cotton seed. Seedcotton also includes varying amounts of leaf, stick, and dirt collectively called trash. After the ginning process, all of the cotton seed and most of the trash have been removed, and the separated cotton fibre is known as lint. Cotton fibre is sometimes recovered from the material removed by lint cleaners towards the end of the ginning process, and this lesser quality fibre is known as mote.

The following discussion classifies actual and possible methods of measuring moisture content in cotton on the basis of the underlying physical process or property. Some of the methods are currently used to measure the moisture content of cotton, others are not but have been used to measure the moisture content of other materials.

3.2 Impact Acoustics

The elastic properties of certain biological materials change with moisture content. Therefore, the acoustic signal arising from a material such as grain impacting on an instrumented plate can be related to moisture content (Mexas & Brusewitz, 1987; Friesen *et al*, 1988; Ruan & Brusewitz, 1988). Seedcotton is singularly unsuited to analysis by this method because of its low density and its softness. However, cotton seed may be suitable for moisture measurement by this method.

3.3 Neutron Scattering

When a source of fast neutrons (*i.e.* certain radioisotopes) is placed in the vicinity of a sample of any material, the neutrons interact (*i.e.* collide or near-miss) with the nuclei of the elements in the sample, elastically and inelastically. Elastic interactions do not slow the neutrons appreciably, but inelastic interactions do. Once the neutrons have slowed sufficiently, they are said to be thermal neutrons and are eventually absorbed by surrounding elements. The lighter the element, the more inelastic the interaction. Hydrogen is the most common light element in most common substances, so the number of thermal neutrons in the vicinity of a suitable sensor and fast neutron source provides information on the proportion of hydrogen in the surrounding material.

In materials like soil, water is the major source of hydrogen in a sample, and this method has been used to measure the water content of soil and soil-like material successfully (the "Neutron Probe"). Although biological materials are relatively high in hydrogen other than that contained in water, and this 'other hydrogen' takes place in interactions with neutrons in exactly the same way as 'water hydrogen', it has been demonstrated that this method is adaptable to measuring moisture content in biological materials with relative accuracy (Wang, 1964).

The method is non-invasive. The time required for reading is substantial, between one and five minutes, so the method is not suitable for online measurement. Although the physical processes of producing and scattering neutrons are not affected by temperature, the method of detecting thermal neutrons is affected to a significant degree. The method requires calibration for the particular material on which it will be used. Calibration should be supplemented by knowing the relationships between moisture content and changes in material characteristics (Parkes & Siam, 1979; Greene & Stuart, 1984; Tollner & Moss, 1995). Thermal neutrons may leak away at adjacent boundaries in the material and be lost to the counting process, so the method is inaccurate close to boundaries in the material (*e.g.* within 200mm of the surface when used in soil) (Hauser, 1984). Consequently it is not suitable for sampling small volumes. Internal non-homogeneity of material may cause greater variation in readings. The method is sensitive to density of the material. It is concluded that this method is not suitable for on-line moisture measurement in cotton gins.

3.4 Gravimetric (Oven Drying)

This method involves weighing a sample accurately, placing it in an oven at 105°C to 110°C for a certain number of hours (depending on the material) and reweighing while still in the oven (Shepherd, 1972). The difference in the weights is the weight of the water driven off. This method historically has been the standard against which all other methods have been compared, and with care it produces accurate results. A quicker variation on this method uses microwave heating but the speed of drying can result in moisture content gradients arising within the material. Consequently the drying process must be broken up into certain periods with mechanical agitation in between, and more labour is required per sample (Sverzut & Verma, 1986). Neither technique is suitable for on-line measurement.

Even though oven drying has been the standard to date, the results using this method can be statistically more variable than results under ideal conditions using newer methods (Byler, 1996). Care must be taken to minimize moisture loss or uptake during collection, storage, weighing and reweighing of the samples. The cotton sample will change moisture content appreciably during delay. Additionally, a large temperature difference between a new sample and its container can cause moisture to leave the sample and condense on the container, making the sample unrepresentative. At the temperatures used in this method, some of the cottonseed oil volatilizes and is lost, and can be seen as an accumulation of gum around the oven vents. The mass of oil lost is an error in the measurement of the dry mass of the sample (Hughs, 1996).

3.5 Nuclear Magnetic Resonance (NMR)

NMR is based on hydrogen accepting energy when radio-frequency (RF) energy is supplied in combination with an external static magnetic field. This magnetic field may be an intense imposed field or it may be, at a minimum, the earth's magnetic field. Once the energy is received and the RF source is turned off, the hydrogen releases the energy in characteristic ways. The duration of the RF pulse is determined according to the strength of the magnetic field and a characteristic coefficient of the hydrogen. The energy released contains information about the amount of hydrogen in the sample, and the degree of tenacity by which it is bound. Hydrogen in free water is bound at a low level, hydrogen in water bound up in the structure of other compounds and hydrogen actually a part of such compounds is bound at higher levels determined by the physical chemistry of those compounds. The result is that the proportion of hydrogen in each type of bond can be measured separately. If, in addition to the homogeneous magnetic field, a magnetic field varying in strength in known ways in two or three directions is imposed then positional information is also encoded. This enables NMR imaging (MRI).

Simple analysis of the released energy (*e.g.* using primarily the Free Induction Decay or FID) is prone to confusion between water content and fat content, and is suitable only for low-fat products such as grain and building products. Sophisticated analysis (*e.g.* including spin echo or SE techniques) is capable of resolving moisture content from content of other hydrogen-rich compounds but is demanding in terms of equipment complexity, operator skill, calibration complexity, and complexity of the analysis (Brusewitz & Stone, 1987; Tollner & Rollwitz, 1988; Tollner & Hung, 1990; Song & Litchfield, 1990; Davenel & Marchal, 1992).

NMR has the potential to provide very accurate results, and is a good laboratory tool. There is no existing technology allowing the generation of suitably homogeneous magnetic fields for the application of NMR to objects the size of seedcotton modules. This is particularly difficult in view of the fact that a cotton gin is an industrial environment with stray magnetic and electrical field. In addition, although the time taken to take a reading is relatively small (*e.g.* less than one second) the time taken to process the data into a single reading is relatively large (*e.g.* approximately one minute using a high-end desktop computer) (Pax, 1996). This is marginal for an application where scanning is required (*i.e.* many continuous readings) and when the measurement is required in real-time to enable smooth operation of a feed-forward measurement system.

3.6 Calorimetry / Thermometry

By putting a known amount of heat into a known mass of material, and measuring the resulting temperature of the material, it is possible to develop a relationship between temperature and moisture content. The method is simple and inexpensive. Moisture content is one of many effects on the resulting temperature of the material. For accuracy, calibration against moisture must be done while keeping all other effects constant. The measurement is therefore prone to errors where conditions differ from those under which the calibration was done. When measuring the moisture content of cotton the result would be affected by the insulating property of the fibre, and it would be difficult to control heat flow to and from the sample while waiting for the measured temperature to stabilize. (Zhang & Brusewitz, 1990; 1991)

A related method is to measure the difference in temperature of the pneumatically conveyed seedcotton before and after a gas burner. By knowing the mass flow rate a relationship can be established between temperature difference and moisture content. This technique is related to a common method of controlling grain dryers, and shares a problem with them in that when the moisture content falls below a critical value, the temperature difference between the two points either side of the burner has no relation to moisture content and overheating can result. This method is attractive because it is inexpensive and well suited to online measurement, however because of the breadth of physical factors included in the calibration it has an upper limit to its accuracy and precision. It would be suited to providing an indication of very_wet/very_dry cotton only. Although this method is not used in industry at present, research is proceeding to improve its accuracy (Hughs, 1996).

3.7 Electrical Conductance

3.7.1 Introduction

This method is historically the most widely used in the cotton industry. Conductance-based methods pass an electrical current, typically at 24VDC, through a sample of lint or seedcotton and relate the current to moisture content by calibration. These methods exploit the existence of an exponential relationship between conductance and moisture content first described by Briggs (1908) (Chang & Kim, 1989). The method is simple, quick, inexpensive, and requires little or no preparation. The first use of this method in meters for automatic control of drying in gins was demonstrated in 1966 (Byler 1992). Meters using this method are available commercially from a number of manufacturers, typically using a cup for discrete sampling or a probe for *in situ* sampling.

3.7.2 Other Factors Affecting Conductance Readings

The individual technique of the operator, the density of the cotton (either in the cup when fitted, or between the probes when fitted), the concentration of dissolved ions in the moisture, the force applied to bring the cotton and contacts together, and the temperature of the cotton have a strong effect on the reading. In addition, when measuring the moisture content of a large mass of cotton such as a seedcotton module, the path of the electrical current is indeterminate. If there is one small path between the contacts which is high in moisture and so passes current readily, the entire mass of cotton will be read as being high in moisture which may not be the case at all. In material such as grain, this shortcoming is overcome by grinding the sample to a uniform powder prior to placing it in the cup, but this is not practical for cotton.

If the meter is manually operated, these factors will mean that readings will vary between operators and between readings from the same operator. If the meter is a fixed installation, the readings will either vary markedly with time with or without changes in the cotton, or the readings will not change to reflect changes in the cotton being measured. Good precise and accurate results have been obtained but these have been under controlled conditions and with a single expert and careful operator. Waldie *et al* (1984) reported that a conductance-based moisture meter in a working gin produced readings with a coefficient of variation of 25 and an r^2 of 0.13. In other words, 36% of the readings were accounted for by the assumed relationship between conductance and the moisture content of the cotton.

The underlying physical relationship between conductance and moisture content is an exponential one, so the range of resistance that must be measured of the range of moisture content of interest (ideally 0% to 25%) is one of several orders of magnitude. It is therefore very difficult to build electronic circuits to measure well both at very low and very high moisture contents. Currently, very dry or very wet cotton must be measured by other means (usually subjective means).

A 100g sample taken for a reading represents approximately 8ppm (0.0008%) of a typical 12tonne module. Consequently the reading, even if it is accurate for the sample, is of questionable accuracy for the module as a whole.

3.7.3 Current Applications in the Cotton Industry

The conductance method is widely used in the industry. Applications include plate sensors in feed control bins, sled type sensors on conveyor belts from the module feeder, and hand-held meters using either a sample cup or bale probes. It is widely recognized that the method has its limitations. However it is inexpensive and the equipment is robust, and it is useful as an indicator of very wet or very dry cotton, and as an adjunct to subjective measurements.

To improve its accuracy, arrays of eight contacts with a larger common earth have been used and readings averaged. The amount of random noise in the signal will be reduced by 65% (i.e. a factor of $1/\sqrt{8}$). However gross errors such as preferential paths, poor contact or short circuiting due to green leaf content will remain. These sensors require a mechanical means to collect seedcotton from a pneumatically conveyed stream and present it to the array, and these are not always successful. During the period over which the seedcotton is accumulated, rapid drying of the stationary sample occurs and this affects the accuracy with which the reading can be related to the stream as a whole.

3.8 Near Infrared Spectrometry and Attenuation

3.8.1 Introduction

Near infrared (NI) refers to the portion of the electromagnetic spectrum around 800nm to 1100nm. This radiation does not cause ionization and suitable sources and sensors both in beam and image form are commercially available and easy to use. The radiation may be sensed after transmission through a sample or after being reflected from the surface.

3.8.2 Near Infrared Transmission

One method of analyzing the makeup of a material using NI is to measure the amount of radiation transmitted through the material (NIT). This measurement may be of the total transmission but more usually it is at selected wavelengths, selected to be weak or strong absorption bands. Materials that are opaque or relatively opaque to visible light may be translucent or relatively translucent to NI and vice versa. Lamb and Hurburgh (1991) used NIT to measure the moisture content of single soybeans. Even with one thickness of soybean, difficulty was encountered in getting enough radiation through the subject to measure, and the equipment had to be modified. Under controlled conditions and using sophisticated mathematical techniques good results were obtained in measuring moisture content. Song *et al* (1995) used NIT spectra on single wheat kernels to determine chemical compositions other than moisture for classification of varieties.

Measuring the transmission of NI radiation has advantages because the path is relatively well defined, however the radiation has poor ability to penetrate a solid so it is not usually a practical method. It may be suitable for measuring moisture content of low density cotton in pneumatic conveying systems, however a limitation here would be in the time taken to resolve a reading from the rapidly moving stream.

3.8.3 Near Infrared Reflection

NI reflectance (NIR) on the other hand has no such problem with penetrating a solid because the measurement is of the NI radiation that is reflected from a sample. NIR is well suited to non-invasively analyzing uniform materials and is an established technique in laboratories and wet manufacturing facilities (Bull, 1993).

However, other problems arise. For example, the surface texture of the sample (*e.g.* seedcotton in a feed control bin) strongly affects the measurement. Also, in effect only the surface layer of that part of the sample in view of the sensor is measured, and this may or may not be representative of the whole sample. The larger the sample, the more important this problem becomes. The density of the seedcotton also affects the reading.

Commercially available NIR sensors have been built into moisture measurement systems cotton gins on an experimental basis (Anthony, 1986; 1991; 1996; Thomasson, 1995). When used to measure the moisture content of cotton online in a working gin it is difficult to view enough of the seedcotton at one time to overcome the sampling problems previously mentioned, except in the fast (28m/s) flow in the pneumatic conveyors. At these points the sensors cannot resolve the radiation quickly enough to be accurate. In the control bin (*i.e.* just after the seedcotton has been gathered by a module feeder and before distribution to the gin stands) the seedcotton moves at approximately 3.3mm/s and the meters have been installed there. Surface texture and density of the seedcotton are approximately constant at this point but they can be expected to vary according to operator habit, feed problems (such as reversing a module feeder), problems with foreign objects, and changeovers between runs of modules from a particular grower.

Waldie *et al* (1984) reported that a NIR-based moisture meter in a working gin produced readings with a coefficient of variation of 19.4 and an r^2 of 0.48. In other words, 69% of the readings were accounted for by the assumed relationship between NIR and the moisture content of the cotton.

This has meant that extra mechanical means have been built into the control bin to ram the cotton down towards the region where the meters are installed so that density becomes more predictable. Also, multiple meters have been installed at different sites in the same stream and readings averaged. Alternatively, extra mechanical devices have been installed to extract a small sample from the cotton feed, control its density prior to measurement, and return it to the stream.

3.9 Dielectric Properties

3.9.1 Introduction

All physical materials have a property called relative permittivity, (ε_r), which in broad terms describes the ability of a material to store energy as an electric field, to absorb RF radiation, and to change the phase of RF radiation. Relative permittivity is a complex quantity, which means that it affects both magnitude and phase. The real part is often known by the older name of 'dielectric constant', and specifies the energy storage capability. The imaginary part is often known as the 'loss factor' and specifies the energy absorption capability.

The relative permittivity of air is approximately 1, and that of water is approximately 80. Consequently, in a material where water may replace air within its structure there may be a useful relationship between dielectric properties and moisture content. Such a method has the advantage of sampling the entire cross-section rather than just a surface layer.

3.9.2 Other Factors Affecting Dielectric Measurements

If a solid material has variable density then the dielectric characteristics measured at high density will be greater than those measured at low density. This is important for biological materials in particular because variable density is usually the case. Density effects can account for as much as 22% of the sensor reading (Waldie, 1983). This effect can be minimized by measuring loss factor as well as dielectric constant because it has been shown under laboratory conditions that relationships exist between moisture content and loss factor, dielectric constant and other measurable attributes of electric circuits which are approximately independent of density (Powell *et al*, 1988; Kraszewski & Nelson, 1991; Lawrence & Nelson, 1993; McLendon *et al*, 1993). Dielectric-based moisture meters in use in industry (*e.g.* for grains) overcome the density problem in part by requiring the user to control the density by packing a standard volume with the material which is ground to a uniform texture prior to reading. Another approach is to control density by mechanical means.

Ionic salts dissolved in the moisture in a material have a strong effect as they interact with the imposed electric current or field and affect the measurement. This effect can be minimized by using frequencies in the microwave range, which is above 1GHz.

3.9.3 Measurement of Samples

Taking samples for measurement precludes on-line measurement but allows the use of hand-held meters. The sample may be placed between conductive plates of various geometries to make a conventional capacitor. The capacitance that results will vary with the changing relative permittivity, which in turn varies with the changing moisture content (Kandala, Nelson, & Lawrence, 1989, 1992, 1994; Nelson, Lawrence, & Kandala, 1991; Nelson & Lawrence, 1992, 1993, 1994a, 1994b, 1995; Kandala, Nelson, Leffler, Lawrence, Davis, 1993).

In the kilohertz range of frequencies, this change in capacitance may be measured by setting up a simple electronic circuit called a capacitance bridge and measuring the change in voltage arising from changing moisture content, to get both dielectric constant and loss factor. Above approximately 1MHz it is necessary to use a tuned circuit which resonates at a certain frequency. As the dielectric characteristics change the circuit drifts off its resonant frequency, and the change can be measured by reference to the extra power to drive the circuit.

Above approximately 1GHz it is necessary to use a microwave cavity in a resonant circuit (Nelson & Kraszewski, 1990; Nelson, Kraszewski, Kandala, & Lawrence, 1992; Kraszewski & Nelson, 1992, 1993; Nelson, Lawrence, & Kraszewski, 1992), where the operating physical principle is the interaction between the material and electromagnetic waves rather than a separate electric field. For both types of resonant circuit, to obtain information about the loss factor it is necessary to measure the Quality Factor ('Q-factor') of the resonance. This measurement involves the relative signal magnitudes at and close to the resonant frequency and is substantially more complicated to perform than the simple counting of the resonant frequency.

3.9.4 Bulk Measurement

For online measurement of moisture content it is necessary to mechanically control an intercepted portion of the flow of material so that its density is controlled. The accuracy of the method therefore depends strongly on the success of those mechanical methods (Zoerb *et al*, 1993; Bruce & McFarlane, 1993).

If a planar sensor is placed against the side of a container with an RF alternating signal imposed upon it, an electric field will be set up which will balloon out into the material in the container. This electric field will be affected by the dielectric properties of the material in the same way as for samples (Waldie, 1993; Waldie *et al*, 1994; Nickell & Henson, 1985).

Alternatively, electromagnetic energy may be freely radiated through or reflected off (Wallender *et al*, 1985) the material of interest. The attenuation of the radiation will be related principally to the loss factor and the phase change will be related principally to the dielectric constant, as before. To measure phase change it is necessary to have a reference channel so that some of the radiated signal passes through the material and some goes direct to the detector. A major complication of such techniques arises from interfaces. At any surface some radiation will be reflected, and this will complicate the magnitude and phase of the signal when analysed. In addition, non-homogeneous material (*e.g.* containing seeds or grains) will cause further complications due to the existence of multiple interfaces at multiple orientations.

Electromagnetic energy may be guided into a bulk material using a transmission line *e.g.* a tube or arrangement of parallel wires. The energy is propagated down the line and will be reflected back by the 'open circuit' (*i.e.* interface) at the end of the line. The reflected signal will be attenuated and phase shifted according to the characteristics of the material lying beyond the interface. Rather than launch an electromagnetic wave at one frequency a recent approach is to launch a sharp voltage step which implies a wide and continuous spectrum of frequencies (by Fourier Analysis). This approach is called Time Domain Reflectometry. Complicated relationships exist between the characteristics of the transmitted energy, the return signal, the dielectric properties of the material and its moisture content. Consequently these relationships are derived by complex calibration.

3.9.5 Applications of Dielectric Methods in the Cotton Industry

The commercially available "Malcam"™ device (manufactured in Israel) operates by freely radiating electromagnetic energy through bales of lint (it is not intended for use on seedcotton). Problems with changing density are overcome to the extent that the density of a bale is controlled. If the density or some other attribute of a bale is appreciably different from the density or other attribute of the bale(s) on which the meter was calibrated then the reading will be in error.

A meter of this type was installed at one gin visited in the US, the Servico gin in Courtland Alabama (one other in the US is known to the author). The meter was installed by the manufacturer and used during the 1995 season. The Servico gin has an experimental program in conjunction with the United States Department of Agriculture (USDA) Agricultural Research Service (ARS) where moisture is measured using conductance-based methods and by oven drying at various points in the gin. Anecdotally, the "Malcam"™ meter was shown to produce useful indications of moisture content, but was consistently in error compared to the other methods by an approximately constant amount. The meter malfunctioned and was removed from service and was not replaced by the early part of the 1996 season. This method would not be suitable for measuring the moisture content of seedcotton because the makeup of the material is less well defined and uniform than for cotton lint.

Lincoln Technology, at the campus of the Lincoln University in New Zealand, have a moisture meter at prototype stage. This meter is based on a dielectric method measuring magnitude and phase. It has been tested on soils and timber with some success. When measuring the moisture content of soil, problems of drift of calibration are overcome by the fact that soils periodically reach saturation. This is a known point in the moisture curve and the meter can readily recalibrate itself every time saturation is reached. When measuring the moisture content of timber, the type of timber is known prior to measurement and so density is approximately known. (It has also been suggested that there is a unique attribute of timber which enables measurement without knowing density accurately, but the details of this are proprietary and cannot be verified.)

When measuring seedcotton, neither of these things are true. Density is very variable. When a module feeder breaks up a module feeder and moves it to the transport system, the cotton in the flow is in a 'conditioned' form and density is relatively constant, especially compared to cotton drawn in manually by suction trumpets. However, this only applies to the cotton when cotton is present. The mass flow rate is by no means uniform until the seedcotton arrives at the feed control bin and so the actual density of the cotton stream is variable. There is a delay in temperature response in drying systems due to the thermal inertia of the equipment. The opportunity to measure moisture content early to overcome this delay in what is termed a "feed forward" system is lost by delaying measurement until the feed control bin. Even at the feed control bin, density is not well controlled, and there will be an inevitable upper limit to accuracy as density varies. It can be said that dielectric-based methods measure density at least as much as they measure moisture.

The requirement for radiation in the MHz or GHz range to overcome the problem of dissolved ionic salts brings with it other problems. The equipment required has close manufacturing tolerances and strict requirements for electrical connections. The method is sensitive to stray electric fields and electronic 'crosstalk'. The robustness of such devices is unproven in an industrial setting. This problem would become larger the larger the scope of the measurement. Setting up a properly defined 9GHz electric field of a suitable size to penetrate a seedcotton module in the presence of high power electrical machinery, large metal structures and other electronic devices for the purposes of accurate measurement would be a demanding task with many unknowns.

3.10 Ionizing Radiation Spectrometry and Attenuation

3.10.1 Introduction

Ionizing radiation (IRad) is an energy flow which has the capacity to cause ionization in material which absorbs it. This ionization is usually accompanied by chemical changes, usually of a destructive nature. IRad may consist of particles with mass (*e.g.* electrons, beta particles, alpha particles, neutrons) or it may consist of electromagnetic radiation (*e.g.* X-Ray or gamma ray), positioned in the electromagnetic spectrum well above ultra-violet frequencies. Only X-Ray and gamma ray IRad are useful for the applications considered here, for reasons of distance of transmission in air and the relative difficulty of generation.

The two types of IRad of interest in this application are X-Ray and gamma ray. The difference between the two lies only in the method of production. X-Ray comes from high voltage high power devices called X-ray tubes, whereas gamma radiation comes from the nuclei of many species of radioisotopes. It is possible to produce X-Ray and gamma radiation in the same range of frequencies.

The advantage of IRad is that it will penetrate solid materials that are opaque to other forms of radiation, at intensity levels that have no measurable effect on the material. Because of the extremely high frequency of the radiation, the volume that is included in the measurement is very well defined geometrically. IRad is present as a natural phenomena in the air, soil, water and man-made objects but only at low levels, so measurement is not prone to inaccuracy due to stray radiation or stray fields.

3.10.2 General Applications of IRad

IRad is used elsewhere in industry for inspection and measurement, for example for medical X-ray imaging, inspection of welds in high pressure vessels and other non-destructive testing of materials. Equipment is available commercially for adaptation to most applications.

IRad has been used experimentally to determine water voids and flows, and density, in soil *in situ* (Tollner & Verma, 1989), and to non-invasively inspect agricultural produce for bruises and voids (Tollner *et al*, 1992). The technique is similar to medical X-Ray Computer Aided Tomography ("CAT scans") and so involves the production of images. A beam method has been used to estimate evaporation rates from forest canopies (Crowther *et al*, 1979)

IRad has also been used for measurement of both density and moisture content of soils *in situ* by means of beams of radiation (Smith *et al*, 1967), (Ligon, 1969). In these related works, by using a high energy source (Caesium 137) wide approximations could be used which simplifies the analysis. This is because at high energies (*i.e.* ultra high frequencies) all materials are almost equally easily penetrated by the gamma radiation. To further simplify matters, and to overcome the problem of needing to know one of density or moisture content to calculate the other, only changes of these quantities is sought instead of actual values.

3.10.3 Potential New Application of IRad to Cotton Moisture Measurement

With the proper instrumentation and analysis, these approximations are not required. The method proposed in NCEA (1996) uses the same basic technology as Smith *et al* (1967) and Ligon (1969) but the scope of the measurement is wider and the analysis more sophisticated. This method is the underlying technology in research proposals to the CRDC by the NCEA in 1996 (NCEA, 1996) and 1997.

The intended method involves the use of X-Ray radiation around the same frequencies as medical X-Ray. In this range, and slightly outside of it, the difference in the abilities of different elements to attenuate radiation is at a maximum so that maximum information is available about the elements present. Hydrogen in particular differs from other elements which is important when moisture content (*i.e.* H_2O) is the main interest. This is a similar attribute of hydrogen to that exploited in NMR and Neutron Scattering mentioned above.

In addition, the intended method involves the measurement of radiation attenuation at many different frequencies within the range. This is a major difference from the methods in Smith *et al* (1967) and Ligon (1969) and is possible because of the commercial availability of 'multichannel analyzer' equipment at reasonable cost.

The analysis is different from all other techniques because of the breadth of information available about attenuation at different frequencies. By looking at differences in attenuation, caused by the different abilities of elements to attenuate the radiation at different frequencies, the relative proportions of those elements in the material being examined can be determined. Where the elemental compositions of the different components making up the material are appreciably different, the relative proportions of those components can be determined.

For seedcotton, those components would be (for example) water, fibre, seed, and trash. The hydrogen in water has characteristics which clearly differentiate it from other elements, as is the case with NMR and Neutron Scattering. Consequently moisture content is the component which is most likely to be measurable using this method.

The analysis is sophisticated but the computing effort is not large. It is estimated that using a medium-specification desktop computer, the computing time would be small relative to other time requirements in the measurement process, and information would be available in real-time. This would enable the use of a feed-forward measurement and control system so that delays in the gin control system (*e.g.* delays associated with the temperature response within the dryers to changes to burner settings) could be compensated for.

3.11 The Issue of Calibration

3.11.1 General Considerations

Calibration is a fundamental issue when deciding the merits of different measurement methods. Calibration is the means by which the raw output of a sensor is made meaningful by comparison with a known standard. Calibration can be simple or it can be complex. All other things being equal, the simpler the calibration, the more robust and practical the measurement method. The more physical processes that can affect a means of measurement, the more complex the calibration.

For example, when using the electrical resistance of a material to determine its moisture content, that resistance is affected by a variety of things. These include the ability of the electronic circuitry to measure electrical resistance in the range required, the pressure with which contact is made, the condition of the contacts, the concentration of ionic salts dissolved in the moisture, the temperature of the material, the temperature of the electronic components, the presence of preferential paths for electric current within the material, the uniformity of the material, the idiosyncrasies of the individual technique, and moisture content of the material.

Because moisture content is only one influence on electrical resistance, when developing a relationship between electrical resistance and moisture all other influences must be held constant or compensated for. If and when any one of those influences changes from those standard conditions and/or the compensation is inadequate, the calibration becomes inaccurate. The more physical processes that are involved in a means of measurement, the more likely it is that one of them will change and inaccuracy arise.

The HVI instrument used in cotton classing is another example of complex calibration. It measures a variety of physical processes such as airflow and light readings ('primary measurements') to measure fibre characteristics such as maturity, shape, and thickness ('secondary measurements'). The primary measurements are chosen because they are attainable whereas the secondary ones are not. The relationships between the primary and secondary measurements are known but they complex, and because they are usually empirical each will have a strictly limited range of validity. Hence such relationships are inevitably open to error (Cui, 1996; Thibodeaux, 1996).

A common consideration in the selection of measurement techniques is a concern about device complexity and hence reliability and maintenance requirements, etc. This is the argument of 'Low tech' versus 'High tech'. However, 'Low tech' does not mean better value in measurement if it means more physical processes are involved, or if it means poorly defined physical processes are involved. Similarly, 'high tech' does not mean worse value in measurement if it means less physical processes are involved, or it if means better defined physical processes are involved.

3.11.2 Calibration Aspects of the proposed Ionizing Radiation method

The IRad method proposed in NCEA (1996) (see Section 3.10.3) exploits the physical process of differential attenuation of ionizing radiation by the elements that make up a material. The calibration which is required to use this differential attenuation to measure moisture content relies on water, fibre, seed, and trash having similar elemental composition from day to day. On simple chemical grounds this would be expected to be true. The method also relies on there being an appreciable difference in elemental composition between water, fibre, seed, and trash, and this would also be expected to be true on simple chemical grounds. The actual degree of difference will be one of the research outcomes when research into this technique is undertaken.

Although this method is not affected by density when measuring, by using the data from the sensors in its simplest form, density can also be measured.

4. CONSULTATIONS WITH THE AUSTRALIAN INDUSTRY

4.1 Introduction and Scope

During August and September 1996, the author traveled to a representative sample of cotton gins and other cotton related locations in south eastern Queensland, and northern and western New South Wales. The following people were consulted for their knowledge of current practice and issues in the Australian industry.

Dalby	**Steve Muhldorff**, supervisor of Queensland Cotton Co. gin.
Cecil Plains	**Evan Layt** and **Ian Cesare**, operations manager and supervisor resp. of Queensland Cotton Co. gin.
Brisbane	**Robert Baird** and **Ian Morrisson**, Queensland Cotton Co. classing.
St George	**Kelvin Bella** and **Tom Willis**, manager and supervisor resp. of Queensland Cotton Co. gin.
Moree	**Ron Jett** and **Duncan McNeil**, manager and senior ginner resp. of North West Ginning Co. gin.
Bourke	**Wayne Brand**, manager of Darling River Cotton Co. gin.
Bourke	**Chris Veness**, supervisor of North Bourke Grower's gin.
Tandou Lake	**Ian Grills**, manager of Tandou Cotton Co. gin.
Warren	**Jim Beale**, manager of Auscott Ltd gin.
Warren	**John Towe**, supervisor of Twynam Cotton Co. gin.

In addition, the Australian Cotton Ginner's Association called a special meeting on 10th September 1996 at the Moree TAFE Ag Skills Centre for discussions in a group setting. Attendance at the meeting was fourteen, including three representatives from the NCEA.

Information was sought in general terms about their requirements for the measurement of moisture content and other attributes of cotton. Other research issues relevant to cotton ginning were also raised. On an individual basis and as a group, there was wide agreement on what the issues were. Where differences existed, they were concerned with the detail only. The issues raised are outlined below and have been grouped under the following twelve headings:

With respect to moisture considerations:

Dissatisfaction with Current Methods of Measuring Moisture Content in Cotton

Quantum versus Incremental Improvement

Overginning less of a problem than Underginning

Minimizing Variations Through Module Grouping
Wet Modules
Sale by Weight when Weight is Variable
Imbalance of Input to Output in Existing Control Equipment
Response Time of Existing Heating Equipment
Wider Requirement for Cotton Moisture Content Measurement

With respect to other issues:
Cotton Standards
Variability in Existing Module Feeder Machinery
General Requirement for Improved Instrumentation (Neps, Maturity, Flowing Density, Trash, Foreign Bodies, Insect Residues)

4.2 Dissatisfaction with Current Methods of Measuring Moisture Content in Cotton

None of the people spoken to were satisfied with current methods of measuring moisture content of cotton, at any point from cotton harvesting to classing and all points in between. The Moree meeting with the Cotton Ginners Association was opened with the simple question "Who is happy with the methods currently available to them?". The discussion that followed was not so much about whether people were happy or not but rather about the number of ways they were unhappy.

Some of the industry people used equipment from the US employing resistive methods and costing many thousands of dollars, but its usefulness was felt to be marginal. The reading was "only a number" which didn't seem to change when it was expected to and at other times changed for no apparent reason. One gin had a module-scale resistive meter which was not serviceable, and had not been attended to because there was no confidence in its usefulness and there were many other maintenance matters to attend to. The hand-held probes used to measure the moisture content of modules and bales gave high readings for MC for very wet modules, and gave no reading at all for very dry bales.

Some gins have automatic systems to control burner settings, based on readings from meters in the seedcotton feed system using resistive methods. In every case the meter reading needed an offset adjustment to perform adequately. It was found that the system had to be overridden from time to time when the drying system was clearly not drying the cotton enough. Learning when to manually override was an important part of establishing smooth operations in a new gin.

There was a great deal of second-guessing in interpreting the meter readings. People were quite prepared to use a resistive probe on a module and to write the reading down as per proper procedures, but they would also smell the module as they walked around it and write a comment alongside the reading if they noticed anything out of the ordinary, *e.g.* a suggestion that it smelt 'hot' or over-wet. A comment from field personnel that a particular module had been picked early in the morning (and hence would have a certain amount of dew moisture within it) was felt to be a more reliable indication of the moisture content of a module than a meter reading. At other times people would use the standard cup attachment on their probe for seedcotton, and would then crack the seed with their teeth to check the veracity of the reading. During ginning operations, the gin supervisors would check the current draw of the ginstand motors, feel the cotton from the front of a ginstand against their cheek, and smell it, and only then would they use the resistive meter to obtain an actual number to record. Gin operations during the season are intensive and experienced operators eventually develop a keen sense of how the machinery in a gin sounds when standing nearby. Consequently it was even felt that standing and listening was a valid way to judge seedcotton moisture in conjunction with current meters.

A common practice is to dry the seedcotton to a very low level prior to cleaning, and then adding moisture prior to ginning so that the moisture content was around the ideal level for ginning. This addition of moisture is separate to the process of adding moisture at the battery condenser prior to baling. The extra expense of drying then moistening is justified on the basis that the cotton cleans better when very dry. However, cotton will still clean adequately at the higher moisture content.

The author has formed the view that there is another benefit from this practice which is at least as important. Cotton approaches 0% moisture content asymptotically because of the tenacity of the bonding of some of the water to the chemical structure of some of the dry content. Consequently 'very dry' is a point on the drying curve which is quite easy to reach without overshoot or undershoot even in the absence of good measurement. From this known condition the operator can then bring the cotton back up to the desired moisture content for ginning in a predictable way. The extra drying and equipment costs of the exercise is difficult to estimate but on an industry scale it would very likely be large.

The degree to which gin operators have learnt to work around their measurement and control shortfalls shows that current methods are inadequate and a great deal of effort is devoted to working around this fact.

4.3 Quantum versus Incremental Improvement

It appears to the author that, paradoxically, from the point of view of gin operators it may not be worth the effort to adopt a means of measuring moisture which is an incremental improvement on the methods already employed if one were to become available.

This result is due to the work-arounds mentioned above. If a new measurement system became available which, while better than current methods, still has shortcomings, a new set of work-arounds would have to be developed for it. The inaccuracies associated with unfamiliarity with the required work-arounds would probably be greater than the improvement in accuracy offered by an incrementally better measurement system. Gin operators have reached an unhappy equilibrium with the current methods, and would most likely want to stay with the "devil they know" rather than adopt a moderately better "devil they don't know".

However, a measurement system which demonstrated a quantum improvement in accuracy and precision, so that there was little to be done by way of work-arounds, would be more likely to be adopted without problems.

4.4 Overginning less of a problem than Underginning

If the gin operator added too much heat or subjected the cotton to more mechanical cleaning stages than was strictly necessary, the cotton suffered heat or mechanical damage, leading to increased short fibre index and lower turnout. In addition, the gin operator incurred extra power costs. On the other hand, the cotton came up cleaner so that it made a better score in terms of colour and trash content. The effects of overginning on the cotton may have been significant but the changes were gradual and were unlikely to cause comment.

On the other hand, if the operator added less heat and/or used less mechanical cleaning stages, there were significant benefits to the cotton owner in terms of turnout and short fibre index, to the gin owner in terms of power consumption and throughput, and to the spinning mill owner in terms of ultimate quality of the textile. However if the cotton came through the gin dirty and trashy so that it was heavily discounted by the buyers, or if the gin saws tripped out due to current overload due to the extra work required to gin moist seedcotton or a blockage, the operator had an obvious and serious problem on his hands. The point at which the gin operation was about to become unsatisfactory was very difficult to judge. Overall, it was better to stay well clear of any chance of acute underginning, even at the risk of chronic overginning.

4.5 Minimizing Variations Through Module Grouping

Gin operators can cope with variations in moisture content if the changes take place at long intervals. If a series of modules with common characteristics is put through the gin, it may take a module or two before the gin operator, with the limited means at his disposal, has the gin process fully "under control", so that the cotton is dried and cleaned only to the required degree. The remainder of the series is then processed with maximum turnout and standard for the grower, and minimum energy expenditure and maximum throughput for the ginner.

If the series of modules is too short, the process may only be close to the optimum for a short time before a new series of modules begins. The proportion of modules processed at sub-optimal conditions will be higher in this case. For this reason it was felt that gins who dealt with proportionally more small growers had a handicap in terms of turnout and profitability compared to gins who dealt with proportionally more large growers.

4.6 Wet Modules

If a module is picked "wet" for whatever reason, so that it is in danger of becoming degraded or even spontaneously combusting, the grower may want it delivered to the gin and put through as soon as possible, before the damage can take place.

From a ginner's point of view, this may not be welcome, for the following reasons:

- If a module is put through earlier under these conditions, the money for that module also arrives in the grower's pocket earlier. The growers whose modules were pushed back in the queue receive theirs correspondingly later. The ginner and the growers in general will not want to reward bad practice at the expense of good practice. Bad practice may involve allowing the picker (who gets paid on the basis of hectares picked only) to pick too fast, too early in the day or too late, or it may involve tardiness in tarping during rain, or positioning modules in low points in the field.

- A very wet module will disrupt the planning of the gin operator and will require a change to the dryer and cleaner settings and the feed rate. It will generally involve the gin operator in extra effort to return the gin process to a settled state.

- The throughput of the gin may drop while the very wet cotton is processed, and the amount of fuel used to dry it properly will be greater. Gin operators report that some wet modules halve throughput and so much moisture is removed that the interior of the gin is coated with condensation. Turnout from these modules is artificially low because the incoming weight of the module is artificially high.

While it is estimated than damage to wet cotton can occur within 24hrs of the module being built, for insurance purposes there is a general requirement that modules do not arrive in the gin yard within 24hrs of being built. This is because cotton has peculiar combustion characteristics, and a fire that starts within a module during building may spread slowly for many hours before it reaches the surface and becomes noticeable. It is preferable that, if a fire is going to become evident, it does not do so in the gin yard and does not spread to other modules which will also exhibit this hidden slow-burning behaviour.

From the grower's point of view, a wet module may be unavoidable. The grower is exposed to weather changes much more than any other party in the production chain, and given a choice between losing cotton on the bush to rain damage and involving the ginner in extra effort, he will generally chose the latter.

In effect, effort in the field has been transfered to the gin. This is not necessarily a bad outcome, as long as it is handled equitably. If quick and accurate measurement of the moisture content of cotton modules was available, the ginner and the grower would have an objective basis for determining the cost of wet modules, which could be passed back to the grower with minimal opportunity for discord.

It was found that ginners in drier areas using irrigated land had less problem with wet modules because rain was less likely to fall during the picking season, although the quality of the cotton from drier irrigated areas was usually higher than for other areas and the drop in value if wet damage occurred was higher as a consequence. Conversely in areas where the rainfall was regular there was a higher likelihood that rain would fall at the wrong time and wet the semi-completed modules and cotton on the bush.

It was also found that the severity of the wet module problem was strongly related to the type of gin. Gins which were part of large corporate growing and ginning operations had few or no wet modules, because their overall management strategy and direct ties of responsibility meant that any problems were fixed quickly or in advance. Gins which were part of cooperatives or which ginned a substantial proportion of cotton from other growers had a larger problem. In these cases some growers were less expert and less able to manage contract pickers, and felt less responsibility for the operations of the gin.

4.7 Sale by Weight when Weight is Variable

Cotton lint is weighed at the bale press in the gin. This weight is combined with the classing information obtained at the merchant's premises from samples taken at the bale press to determine the value of each bale. A bale at the standard weight of 227kg at 8% moisture content contains 18kg of water. The standard 8% value used in the industry originated from the fact that cotton lint stored in the traditional growing areas in the southern states of the US tends to equilibrate to this moisture content. In many areas this moisture content has been reached by putting the lint through a device which puts in extra heat and water, raising the moisture content of the lint from the 5.5% to 6.5% which is best for ginning.

Cotton gins in Australia tend to be located inland where the air during the ginning season is relatively dry. Cotton merchants on the other hand tend to be in capital cities on the coast where the air is relatively moist. A bale which weighed 227kg at 8% in the gin may only be at 4% by the time it is transported to the coast, and weigh only 217.5kg. (Some gin operators stated that thousands of litres of water per season went into cotton in batt form just before baling but using current methods they were unable to detect any moisture in the bales after being in storage at the gin for a week or so.) If the bale arrives at the merchant in that condition, the merchant will generally notify the gin that the bale was underweight and adjust the price accordingly. It is likely that the bale will pick up moisture during storage, and may reach 8% to 10% after a period. At 10% the bale weighs 232kg, so in fact there has been no loss.

If there was an readily available accurate method of measuring the moisture content of a bale then weight could be quoted accurately at a certain moisture content. Consequently, the underlying dry weight of the bale and its value would be known whatever the moisture content of the bale subsequently became. The uncertainty about bale weights and values would not arise, and it would not be necessary to put in the extra heat and water prior to the bale press.

4.8 Imbalance of Input to Output in Existing Control Equipment

Most gins have sophisticated control gear including Programable Logic Controllers (PLCs) to control the electrical switching of gas burners and large variable speed electric motors. The electricity bill for a season in a large gin may be of the order of one million dollars, and the gas bill may be two hundred thousand dollars. The more modern gin control rooms are soundproofed, airconditioned, with CRT screens and LCD readouts. On inspection, the PLC equipment typically has 30 to 40 output channels available, and most of these are in use connected to relays and contactors throughout the gin, replacing manual switches and bringing control to a central point. However, while there are the same number of input channels, these are typically only be connected to one or two temperature overload sensors and possibly online resistive sensors at one or two points in the transport system. It was noted that often these were disconnected.

These observations point to a pronounced lack of information feeding into the control room (apart from the human senses). The process is complex, the running costs are high, the equipment expensive and finely adjustable, and the product is high in value, but a major part of the technology which would be expected to be present is missing.

4.9 Response Time of Existing Heating Equipment

Where automatic systems controlled the gas heaters for drying, the response time of the drying system (dependent on the heat sink ability of the mass other than cotton heated by the burners) was significantly longer than the time it took for wetter cotton to pass through the driers, so that the operator had to act in advance when it was known wet cotton was about to appear. Rather than under-dry the first part of the wet cotton, the decision is made to over-dry the last part of the previous cotton

4.10 Wider Requirement for Cotton Moisture Content Measurement

The people in the industry that were spoken to felt that better methods of measuring moisture were required along the entire cotton production chain, from field to spinning mill. For example, in a cotton picker it would be useful to know the moisture content of the cotton going into the hopper, because this would indicate when the picker was covering the ground too fast and picking up too much leaf, and would also indicate if the picker is operating too early or too late in the day when dew is on the leaves. In a gin, such a measurement means would indicate wet modules, the required setting of the burners, and the amount of water to add to bring a bale up to standard moisture content for baling. It would provide a check on bale weights for a merchant, and provide more rigorous control of moisture content during classing and spinning.

4.11 Cotton Standards

Current cotton standards are based on a combination of subjective human judgement and the use of proprietary equipment. The output of this equipment is constant within limits and is reliable enough to serve as useful standards. However, the output relies on empirical relationships, has no strict analytical or physical basis and cannot be meaningfully related to other measures.

The equipment measures those attributes of the cotton that can most readily be measured. However, the equipment cannot replicate the sophisticated subjective analysis that humans can, nor can it weight the importance of each class of measurement in a given situation. If a prospective buyer believes that one group of attributes overrides another, the standards may be bypassed. This is only as it should be and demonstrates a beneficial flexibility in the system. However, some anomalous situations can arise, for example as follows:

> Cotton may be cleaned to a lesser degree because the gin seeks the practice of "gentle ginning" and less cleaning equipment was online at the time. This cotton lint may contain enough large leaf trash such that the Trash Score is reduced. The fact that the cotton has been subjected to less mechanical cleaning, particularly post-gin stand cleaning, will mean that the Short Fibre Index (SFI) will be better than usual. Less mechanical damage has been inflicted on the fibre and less fibres have been broken into shorter lengths (Anthony, 1996). In addition, the Reflectance of the cotton may be poorer not because of any real discolouration, but simply because it has undergone less combing and the cotton remains in the locks that were separated from the seed rather than in a uniform combed mass. There is a limit to the extent to which an improvement in SFI can balance a deterioration in the Trash Score and Reflectance so the grower receives a price penalty.
>
> However, a representative of a spinning company may look at the same cotton and decide that, regardless of standards, large leaf trash comes out in the spinning process relatively easily so the Trash Score is of less consequence. The representative may also recognize that the 'preparation' of the cotton has artificially diminished the reflectance and colour (Thomasson, 1993; Anthony, 1994), and that the improved SFI is a very good outcome because the quality of the resulting cotton yarn will be higher. The cotton may then be sold at a discounted price to a buyer who knows he is getting above-average cotton.

The standard measurement known as 'preparation' was of interest in pre-mechanization times when cotton gins did not possess the amount of drying and lint cleaning machinery found today (Gerdes, 1941). Poor preparation was a sign that the cotton had not been dried sufficiently in the gin, and that the bolls had not opened and aerated enough to shed trash. Preparation was an indicator of moist and trashy cotton rather than a useful measurement in itself. The problem being encountered now is that ginning cotton gently to preserve its quality results in cotton that keeps the individual identity of each lock through the process. In addition, it is preferable in quality terms to provide extra seedcotton cleaning for lint cleaning, but in preparation terms lint cleaning is desirable because it produces well-combed and uniform cotton lint (Columbus & Anthony, 1991). This means low scores on preparation even if the cotton is dried and cleaned properly, and the quality is higher than it would otherwise have been (Mayfield *et al*, 1995).

The cotton ginner is bound to gin to maximize returns for the grower, even if this results in poorer quality lint cotton. As soon as the ginner makes the effort to increase quality, he runs the risk of severe price penalties because the preparation does not meet "the standards". The discount may amount to US $30 per bale. This is a difficult issue for grower, ginner, and spinner.

Large growing operations who produce sizeable amounts of cotton (thousands of bales) with a common history in the field and in the gin are able to form a relationship with buyers so that they do capture the increased value of good cotton falling outside of normal standards. However, growers not able to do this may have their cotton being sold at far less than the real value to the buyer.

This is relevant to a discussion on measurement systems because of the effect of the lack of objective means of measurement. Competitive business practices will generally mean that, given a choice, buyers will adhere to those standards which provide the best buying price. The grower and the ginner have no objective means to show that their cotton is good cotton if the usual standards say otherwise. If they had a measurement means to objectively state that the trash was large leaf trash rather than pin trash, and in addition to an SFI index had a rapid measurement of neps and other indicators of underlying fibre condition, they would be in a better position to accurately and objectively state the quality of their cotton.

This may ultimately mean that new standards need to be developed based on new and better means of measurement. The less these standards are fashioned according to measurement shortcomings, and the more they are fashioned according to the needs of the customer (spinning mills), the more useful they will be.

4.12 Variability in Existing Module Feeder Machinery

It was found that there is great variation in the layout of equipment in gins where the cotton modules are fed into the pneumatic transport system. Three main types of module feeders were inspected; moving head, fixed head, and twin fixed head.

The moving head type is mounted on rails so that it moves along a series of three or so modules placed in its path by module handling equipment. Just before the last module is consumed, the gin operator speeds up the progress so that the main control bin is full and the conveyor has a heavy load of cotton. This cotton keeps on feeding the gin while the module feeder reverses and a new series of modules is put in place. Subject to the skill of the gin operator, there is no break of input to the gin.

The fixed head type is rigidly mounted and a mechanism in front propels modules toward it. The mechanism may be a walking floor where the slats are divided into thirds so that while two-thirds are moving the module forward the other third is reversing to maintain continuous motion, or it may be a conveyor chain. As long as the workers keep feeding modules onto the mechanism, feed to the gin is uninterrupted. The operator skill required for this is less than that for the moving head type.

The twin fixed head type is relatively new, and consists of a two sided mechanism that can consume modules whilst moving in either one direction or the other, but not both together. When the feeder reaches the end of one run, doors close around the last portion so that it does not topple. Doors on the opposite side open and the feeder moves back on the new series of modules which has been placed or is being placed behind it using conventional module handling equipment.

Each type of module feeder would have different design problems for apparatus to measure moisture content of whole modules. For instance, methods using microwave RF radiation and ionizing radiation would require that personnel are absolutely excluded and substantial shielding would be required.

4.13 General Requirement for Improved Instrumentation (Neps, Maturity, Flowing Density, Trash, Foreign Bodies, Insect Residues)

Gin operators felt that they would like to be able to cut lint cleaners and impact cleaners out of operation to improve the quality of cotton fibre produced, and to use less heat to dry it to the proper level for ginning. However, by the time trashy cotton was seen at the bale press, or the ginstands overloaded due to wet cotton, it was too late to save that particular bale from discounting. There is currently no practical way to measure trash or moisture in a timely manner, and the gin operators therefore had no confidence when it came to experimenting.

If there was a way to measure of the density of cotton being fed into a gin this would provide a means of automatically controlling the feed rate of a gin.

In addition, it was strongly felt that it was extremely difficult to institute a worthwhile quality control system in terms of neps, maturity, trash, and foreign bodies in the absence of good instrumentation. There was little or no information with which to work.

Ideally, people wanted to have quick and accurate means to measure neps, maturity, the flowing density, trash content, the presence of foreign bodies, and moisture content.

5. CURRENT PRACTICE AND RESEARCH IN THE U.S. COTTON INDUSTRY

5.1 Introduction and Scope

Between 22nd October and 14th November 1996, the author travelled to the United States. The objectives of the trip were as follows:

- investigate current practice in cotton ginning.
- determine the attitudes of industry personnel to the importance of moisture measurement methods, and to current methods of measuring moisture.
- develop an understanding of the position of Australian ginning in relation to their US counterparts.
- visit a comprehensive list of research facilities to obtain a first-hand view of past and present research on cotton-related issues, and to form a picture of research that might be pursued in the US in the near future.
- obtain published and unpublished research literature not readily available in Australia.
- make personal contact with relevant personnel engaged in cotton research in the US with a view to future cooperation.

The author visited onsite and spoke to staff of cotton gins, cotton broking companies and companies manufacturing cotton ginning machinery in Fresno CA, Dos Palos CA, Firebaugh CA, Visalia CA, Shafter CA, Safron Valley AZ, Courtland CA, Lubbock CA, and Columbus GA. Discussions were primarily about measuring cotton moisture, but broader issues were also discussed as they arose.

In addition, the following research facilities were visited: ARS Cotton Laboratory, Phoenix AZ; ARS Cotton Laboratory, Mesilla Park NM; ARS Cotton Laboratory, Stoneville MS; ARS Fiber Laboratory, New Orleans LA; ARS Sensing and Instrumentation Laboratory, Beltsville MD.

5.2 Current Practice in US Cotton Ginning

5.2.1 Methods of Measuring Moisture in Cotton

Moisture meters employing resistive measurements are commonly used. The users feel that these meters give an indication of over-wetness or under-wetness rather than any meaningful number representing a moisture content. Typically about 50% of the decision regarding the moisture content of cotton is based on a meter reading, the remainder is subjective by the operator. The automatic devices which act on the seedcotton being fed into the feed control bin show sharp spiking of the reading when green leaf trash is present which reduces the accuracy but does give a clear indication of the presence of the green leaf trash. Some operators have installed conductance-based meters and have either removed them after a period or have not maintained them.

A few 'early adopter' operators (*e.g.* Burdette Gin, Leland MS & Servico Gin, Courtland Alabama) have multiple conductance-based meters installed as part of experimental process control systems. These have been expertly installed and maintained by the researchers responsible for their development and give acceptable results, although there remains a problem with staff in the gins not believing the meter when it is right, or believing it when for whatever reason it is wrong.

These systems overcome problems with attaining proper contact with the cotton by mechanically collecting samples at intervals and pressing these against the meter contacts (the "Paddle Meter"). One problem with this is the extra mechanical complexity, and the need to build the sampling process into the process control algorithms. Another problem which has not yet been overcome is the fact that while the mechanical sampler is gathering a sufficient sample for measuring, the cotton lodged on the paddle is stationary in a fast hot air flow. Drying takes place rapidly and the reading ultimately obtained is probably not representative of the cotton stream.

5.2.2 Working Around Measurement Problems

Gin operators in the US work around moisture measurement in much the same way that Australian gin operators do. They try to make their runs as uniform as possible, either by their own management practices or by maintaining links to "their" growers and knowing the history of a module. They use their own senses to check the apparent reading from their meters at all times. Some dry to less than 4% for cleaning then add heat and moisture, or even steam from boilers, to bring it back up to proper ginning moisture levels. Overall, they find it better for their purposes to chronically overgin than to acutely undergin, because they encounter problems with meeting parts of the USDA standards when they try to gin for quality cotton.

5.3 Current Research in the US

5.3.1 Near Infrared and Conductance

Research in the US regarding moisture measurement is taking place at the Stoneville ARS Cotton Lab, near Leland MI. There are two technologies being investigated, NIR and a more sophisticated conductance-based application, under the direction of Mr WS Anthony and Dr Richard Byler respectively. (The strengths and weaknesses of these technologies are outlined in Chapter 4.) The work is located both at the experimental gins onsite, and at collaborating gins in the US, and this has been going on for approximately 10 years.

The NIR work is now part of a larger group of projects, combining moisture, trash, and colour measurements (Anthony, 1989; Anthony, 1990; Thomasson & Taylor, 1991; Thomasson, 1992; Byler & Anthony, 1992; Thomasson *et al*, 1993; Anthony *et al*, 1995; Anthony, 1996). At this stage the systems are in the early stages of commercial release. The author believes that because of the detailed requirements for installation and operation, adoption elsewhere in the US industry will be gradual.

The conductance work is undergoing service trials at the Servico gin in Courtland Alabama. This work is also part of the process control work at the Stoneville ARS laboratory. The meters are distributed throughout the gin providing multi-point control of the process via software and a computer interface.

It is emphasized by the people concerned (both in manufacturing and in research) that neither of these measurement technologies are intended to produce intrinsically accurate readings. Rather, these meters are intended to provide useful indications which can help improve the control stability of the ginning process. Dr Richard Byler, who is responsible for this work, made the comment to the author that an accurate Australian method would co-exist in a working gin with the simpler and cheaper American methods. Te latter would be used at various points in the ginning process where the cotton is not in a module form, and provide an indication of "state": their readings be cross-checked with the former to retain calibration.

5.3.2 Calorimetry / Thermometry

Mr Ed Hughs at the Mesilla Park ARS Cotton Lab has adopted a simpler approach. This lab is primarily involved in developmental work on commercially available gin equipment, and has incorporated into this a program to measure the temperature change caused by a burner relative to fuel use and cotton flow, as a means of indicating moisture content.

5.3.3 Harvesting and Ginning Equipment

The ARS Cotton Lab in Lubbock TX is concerned with research into harvesting and ginning equipment. Mr Weldon Laird has developed a 'belt dryer' which decouples cotton drying from cotton transport. It is felt that a lot of energy is wasted when drying cotton because adding heat outside cotton bolls does not necessarily mean that heat is delivered to the inside of the bolls where the moisture is found. Samuel Jackson Inc, also in Lubbock, have a fountain dryer which addresses this by involving the cotton in a 'high shear' action where the speed differential between cotton and air is maximized. The belt dryer takes this further by dropping the cotton out of the air flow onto a chain belt driven at low speed. The drying time can then be extended without risk of blockages, reducing the temperature gradients and the risk of burning, and substantially reducing power requirements. The air flow is at right angles to seedcotton flow for best drying action. Although it is being commercially manufactured it is not widely known in the industry. Work is also proceeding at this facility to improve saw cleaners on cotton strippers.

Lummus Corp in Columbus GA is proceeding with work into a third type of ginstand, after the saw gin and the roller gin. Called the cage gin, it involves a mechanism similar to the cage and rollers in a conventional roller bearing, except on a large scale and with every second roller driven backwards. The seedcotton is drawn onto the outer surface by airflow as with a battery condensor. The lint is caught up and drawn through leaving the seed outside, a gentler method than saws but faster than rollers.

5.3.4 Other

The ARS Sensing and Instrumentation Lab in Beltsville MD is conducting research using Near Infrared Reflectance, but not with cotton. The work that is ongoing is concerned with wholesomeness and quality of poultry and fruit, chemometry and grading of grains and other products, and a variety of strategic projects in agricultural applications other than cotton and/or moisture.

5.4 US Industry Recognition of Need for Emphasis on Cotton Gin

Mr Don Van Doorn, Senior Vice President of Lummus Corp, made the informal comment to the author that, provisionally, the Research Committee of the American Textile Manufacturing

Institute (the peak body in the American textile industry) have agreed to finance further research into the cage gin concept to solve mechanical reliability aspects. This has been done as part of their recent adoption of the principal that the **cotton gin** represents the best avenue for improvement in cotton quality in the U.S. That a body representing many millions of dollars of investment and production has come to such a view gives it substantial weight.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

1- The Australian cotton industry is widely dissatisfied with current methods of measuring moisture content in cotton.

2- These current methods are limited by the physical processes on which they are based, and future improvements are likely to be incremental and unlikely to alleviate the dissatisfaction previously mentioned.

3- The new method of measuring moisture content proposed in NCEA (1996) has the potential to overcome present problems in measuring moisture content. The method offers benefits in improved cotton quality due to less overdrying and heat damage, and a reduction in the amount of energy lost when overdrying cotton. Another benefit is that the method makes full process control of cotton gins more feasible, where it was arguably not feasible beforehand due to a lack of accurate information on moisture content, the major influence on cotton once harvested.

4- The MMS method proposed in NCEA (1996) once developed could be applied to other points in the cotton production chain with a minimum of modification. This would answer another need identified within the industry for better means of measuring the attributes of cotton, so that quality control systems can function properly. In addition, the method underlying the MMS could remove current ambiguities with the weight and value of cotton bales where the value is related to weight which varies with moisture content which is difficult to state accurately.

5- Nothing has come to light during investigations in Australia and in the USA that would suggest other groups are carrying out similar work, or are contemplating similar work.

6- The US cotton industry shares the Australian industry's dissatisfaction. The comment was made to the author by a senior technical manager of a large multinational cotton growing, trading and spinning company that "if it works, we will invest in it". This was in the context of discussing that company's strict policy of requiring a firm level of return on investment for every item of equipment.

7- An improved method of measuring moisture content would be saleable in the US industry. The US industry has identified at a high level the need to improve the performance of their own gins, and moisture content would be included in this. This offers a means of reducing the Australian industry's technological dependence on the US. In this way, research costs in Australia could be recouped in part from sales to the US instead of vice versa.

6.2 Recommendations

It is recommended as follows:

(i) That research be undertaken to develop a module-scale moisture scanner based on the use of ionizing radiation, as outlined in the NCEA research proposals to the Cotton Research and Development Corporation in February 1996 (NCEA 1996) and 1997.

(ii) That, once the measurement system is proven, research should be undertaken to incorporate the technology within the process control of cotton ginning.

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