



RESEARCH REVIEW No. 15

**MOISTURE CONTENT OF
CEREAL GRAINS**

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HGCA RESEARCH REVIEW No 15

MOISTURE CONTENT OF CEREAL GRAINS

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ABSTRACT

The moisture content of cereal grain has important implications for quality whatever the intended use of the grain. The vulnerability of grain to biodeterioration by its own metabolic activity, or by the action of insects, mites or moulds, is strongly related to moisture content. In addition, physical properties such as hardness, coefficient of friction, specific weight and electrical characteristics are also influenced by moisture. All of these ultimately influence the commercial value of the crop in as much as they affect the cost in meeting trading standards, the storability, the ease of handling of the crop, and indeed (in the case of electrical properties) the means of measurement of moisture content.

Moisture can be present in grain in more than one state, i.e. as bound, adsorbed or absorbed water, but the definitions of these forms are not clear. Indeed even the definition of moisture content is arguable. A working compromise is "the amount of water in a product that can be measured by a specific method" and this allows certain general statements to be made about grain deterioration:

(i) Below about 15% moisture content (wet basis) and 15°C little metabolic activity occurs.

(ii) Above 16% moisture content, enzyme activity increases even

at low temperature.

(iii) Storing above 16% moisture content is not recommended unless steps are taken to prevent mites, mould and metabolic activity.

As these observations indicate, there is a relationship between moisture content and grain temperature in respect of biodeterioration. In general, biodeterioration can be slowed down or inhibited by reducing the temperature. However, the processes of deterioration produce heat, sometimes more rapidly than it can be lost by natural or even artificial cooling.

The development of mites and moulds is related to the relative humidity of the intergranular spaces which is, in turn, controlled by the moisture content and temperature of the grain. The effect of temperature on safe storage may often not be fully appreciated: grain at 14% and 25°C is in equilibrium with air at 65% rh, but so is grain at 15% and 5°C. Therefore, in relation to the prevention of moulds and mites, cooling can be equivalent to drying. Unfortunately, most of the common insect pests of grain found in U.K. can develop at moistures of less than 14%, so that reducing intergranular relative humidity alone may not provide an economic answer to all problems of infestation. The proper combination of both cooling and drying will, however, make grain safe from all forms of biodeterioration.

Accurate determination of moisture content is a vital part of grain conservation. A range of benchtop and portable instruments is commercially available. Most rely on the determination of an electrical characteristic of the grain (measurement of conductivity or capacitance), which is related to the moisture content. These instruments must be calibrated to interpret the electrical measurement as moisture. This is done by comparing meter readings with data from standard oven determinations made on the same sample. This process is complicated by the existence of a number of different standard methods. These, which are all based on weight loss of oven

heated samples, can give answers differing by as much as 0.7% moisture content.

There is an urgent need for a single standard (preferably BS 4317, part 3, 1987) to be adopted by all members of the grain trade and for all moisture meters to be calibrated against this standard and suitably labelled.

Recent developments with methods of continuous moisture measurement have brought nearer the introduction of on-line moisture measurement for the control of driers using capacitance-based instruments. This should improve drier performance and reduce the cost of grain drying. An alternative method, based on microwave attenuation has been successful on a laboratory scale, but is sensitive to bulk density variations in flowing grain.

Near infra-red reflectance is not a promising contender for materials whose thickness exceeds the depth of penetration of the radiation. Nuclear magnetic resonance, however, has been shown to give excellent agreement, in laboratory tests on wheat and barley, with oven determinations.

Marketing standards for grain vary from section to section of the grain trade and from year to year, according to the current economic situation and the needs of the moment. Acceptable levels of moisture content sometimes exceed those which are consistent with safe storage, but the general trend over the years for specified moisture contents has been downwards. This must have led to increases in the cost of pre-storage conditioning, but produced improvement in the overall quality of grain.

The variable costs of drying grain are attributable almost equally to the cost of fuel and the loss of weight of the crop. To dry 1000 tonnes of grain from 16% to 14% moisture content "costs" about £4,000.

Whatever standards for moisture are imposed, representative samples are a prerequisite. There is little published literature on the subject of sampling, and even among experienced members of the industry, discrepancies in quality assessment can arise because of the lack of recognised standards. The lack of research in this area, particularly in the U.K., could seriously hamper progress towards better methods of measuring moisture content and other quality factors.

The measurement and significance of moisture in grain appear to be poorly understood. This situation is aggravated by the apparent disagreement which arises from the use of different moisture meters, or meters calibrated to different standards, on the same samples of grain.

In the light of the above comments it is possible to draw up a list of positive suggestions which, if implemented, could help to improve the efficiency of the grain industry and to reduce disputes between buyers and sellers of grain:-

1. Information on the effects of moisture and its measurement needs to be more widely disseminated to farmers and storekeepers and better guidelines on the calibration and maintenance of moisture meters should be provided.
2. BS 4317 should be adopted as the basis for all moisture determinations and meter calibrations.
3. There is a need for a standard test protocol for moisture meter testing. This should be coupled with the establishment of a national testing agency and the establishment of regular, routine ring testing of meters and oven methods.

4. Co-operation between manufacturers and research organisations in the development of on-line moisture measurement would speed the development of practical instruments.

5. The most promising new method of determining the moisture content of cereal grains would appear to be Nuclear Magnetic Resonance. Research on the development of a standard method based on this technology is required.

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Glossary of terms

ASAE	American Society of Agricultural Engineers
Biodeterioration	Deterioration caused by a biological agent, eg insects, mites or mould
BSI	British Standards Institution
erh	Equilibrium relative humidity
GAFTA	Grain and Feed Trade Association
HGCA	Home-Grown Cereals Authority
ISO	International Standards Organisation
NFU	National Farmers' Union
rh	Relative humidity
UKASTA	United Kingdom Agricultural Supply Trade Association Ltd.

Chapter 1 Introduction

Terms of reference:- This review is confined principally to the measurement and significance of moisture content in cereal grains at levels encountered during storage under U.K. conditions. All moisture contents quoted are on the basis of percent wet weight, i.e. the weight of water expressed as a percentage of the weight of the grain together with the water it contains. Grain at moisture contents in excess of 18% will not be discussed except in the context of measurement needs prior to and during drying. Grain stored at high moisture contents with the aid of fungistats or held in hermetically sealed silos is also considered outside the terms of reference. The grains referred to are principally wheat and barley but there is a limited reference to oats, rye, triticale and maize. The Review also covers current methods of measurement and the importance of moisture in biodeterioration.

A major objective of the review is to identify future needs and developments in terms of R&D. Commercial requirements are reviewed in the light of current R&D and quality standards so that guidelines can be drawn up to assist in channelling research resources in the appropriate directions.

It is often intimated that all problems relating to moisture content in stored grain can be linked to problems in measurement. This point of view misses totally the vital question: why are moisture contents measured? In fact, moisture has a fundamental influence on the properties and commercial value of all cereal grains. Some of the key properties that will change according to the moisture content of the grain are listed below:-

Biological

Biodeterioration - insects, mites and moulds.

Germination - dormancy, malting properties.

Metabolism of the grain - production of heat, weight loss and enzymic activity resulting in rancidity etc.

Degradation of pesticides.

Physical

Texture - hardness, seed size, compressibility.

Surface friction - angle of repose.

Drying.

Handling - ease of flow, friction, viscosity.

Specific heat and entropy.

Specific weight.

Milling properties.

Air-flow through grain.

Electrical properties.

Commercial

Costs in meeting trading standards - intervention, export, etc.

Capacity of store.

Cost of drying and storage.

The amount of water present in grain determines the rate of metabolism of the seed and also controls the onset of germination. Dry grain (<12% moisture content) has a very low level of metabolism, but at moistures above 20% enzyme systems are active and above 25% the process of germination is likely to be

initiated. Generally, storage of more than a few weeks cannot be contemplated at moisture contents above 16%. Conversely, at 12% or less grain is extremely durable and can be stored for several years without loss in quality or quantity, provided insect pests can be excluded (PIXTON, 1980).

Water may be present in grain in three forms:-

i) bound water or water of constitution forming a chemical union with the components of the grain.

ii) adsorbed water which is closely bound to the adsorbing substance by molecular attraction, but less firmly held than bound water.

iii) absorbed water which is held only loosely in the fine extra-cellular spaces by capillary action. The capillaries begin to fill at about 75% rh (PIXTON, 1982).

The influence exerted by these different forms of water on methods of measurement and on biological activity is not clearly defined. However, it is generally considered that only the adsorbed and absorbed water are measured and affect biological activity. In practical terms, it is usually difficult to separate the three, so all may be included in the broad term of moisture content.

The terms "bound water" and "free water" are often used to describe the categories of the water in grain. However, a technical definition of these terms has proved difficult to establish by reference to published data. KRETOVICH (1945) defined bound water as "water that cannot serve as a solvent or medium in which biochemical changes can occur". He also introduced the term "critical moisture" which is "the limit of moisture above which free water appears in the grain, as a result of which a strong tempo of fermentation processes begins". The term "free water" is most often used to describe absorbed and adsorbed water (HALL, 1970; PIXTON, 1982). Even the provision of a technical definition for "moisture content" was very difficult. The authors suggest

that, for practical purposes the best definition might be:-

" the amount of water in a product such as grain, that can be measured by a specific method".

However, it must be borne in mind that different methods will measure proportionally different amounts of water in the three categories and are, therefore, likely to produce different results (see Chapter 3). Despite this problem, no better, simple definition can be constructed, so the one given above will be used in this review.

The development of all agents of biodeterioration, but particularly Astigmatid mites and micro-organisms, is directly related to the availability of water, which is controlled by the moisture content and temperature of the grain. At moisture contents above 16%, rapid fungal growth is likely which can result in a serious loss of quality and even lead to contamination by toxins. Mites will develop at moisture contents of 15% or more and, if present in sufficient numbers, will also result in a loss in quality. Insects are less dependent on the moisture content of grain but levels below 10% will inhibit many species and slow the rate of reproduction of those that are able to complete their life cycles. Temperature interacts with moisture to influence biodeterioration, so the understanding and interpretation of moisture content data, in relation to other physical parameters of the grain, is an important factor in ensuring the safe storage of cereals.

Water content affects the physical properties of individual grains and grain in bulk. Dry grains are more prone to shatter during transportation but have a higher bulk density and thus pack more closely than more moist material (DUTTA et al., 1988; LAWTON and MARCHANT, 1983). It is widely thought that conveying systems will move dry grain more rapidly but are likely to cause more damage and create more dust than when handling wet grain. However, only limited supporting evidence could be found in the scientific literature (McLEAN, 1980). Changes in these physical properties will affect storage cost and quality after storage .

The amount of water in grain also features in commercial dealings, with some processors requiring grain within specific ranges of moisture and others setting maximum levels to restrict the amount of water in grain that they purchase. Within the U.K., several trading standards specify maximum moisture contents and failure to meet these may result in a financial penalty or rejection of the offered load. Unfortunately, confusion and dispute between buyer and seller may arise because the contracts do not always specify the method by which the moisture content is to be determined.

Much research has been directed at developing methods of measuring moisture in grain. However, differences between the results produced by different methods still remain, and these are not fully documented (see Chapter 3). The physical and biological consequences of water in cereal grains can only be predicted if the water requirements of the whole range of pests and micro-organisms are known and these data are related to the moisture content (as determined by a standard method) and temperature of grain. The complexity of this interaction is not always fully appreciated and, in any case, commercial requirements may, on occasions, override the biological parameters for safe storage.

Chapter 2 The influence of moisture on biodeterioration.

A. General

Water is an essential component in the metabolism of all life forms. Therefore the presence and availability of water has a controlling influence on any changes that may occur in grain during storage. These changes may be a direct result of activity within the grain or may be produced by external sources of biodeterioration. The availability of water is affected by temperature so both must be considered when making predictions about biological phenomena.

B. Effects on the grain

The moisture content will affect the rate of metabolism of the grain and control development of the embryo. Below about 15% moisture content and at temperatures below 15° C, little activity occurs, so that grain can be stored for long periods without loss of weight or quality, provided agents of biodeterioration are kept at bay. PIXTON (1980) reported that English and Canadian wheat, with a moisture content of 12%, lost little in terms of baking quality after 18 years storage. However, at a moisture content of above 16%, enzyme activity within the grain increases rapidly even at low temperature. These changes may render the grain unsuitable for many commercial uses (LINKO, 1960). It is extremely difficult to predict weight or quality losses caused by the grain metabolism under these conditions as they are heavily influenced by temperature and often masked by the activity of moulds, mites and insects. Storing grain at moistures in excess of 16% cannot be recommended unless specific steps are taken to prevent the development of mites and moulds, and to prevent or suspend the metabolic activity of the grain.

Attempts have been made to quantify weight loss in grain at

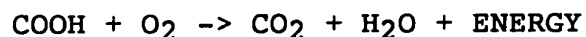
elevated moisture contents but results are hard to interpret as authors do not seem to use experimental procedures that allow losses caused by micro-organisms to be separated from those caused by the respiration of the grain. Authors may also fail to take account of the influence of temperature on the availability of water. In practice, the cause of loss is unimportant so the estimate given by STEELE and SAUL (1962) of 31% loss in weight after 6 months storage at 21.5% moisture content can probably be regarded as realistic. At a moisture content of more than 25% the process of germination will commence. Below this level but above 16%, many of the enzyme pathways within a grain may be active.

Moisture in the grain, together with temperature, also controls the activity of agents of biodeterioration. The development of, for example, moulds, can lead to the production of sufficient metabolic water to initiate enzyme-based reactions within grains. Thus, the enzyme activity within grain can be initiated by biodeterioration rather than solely by the initial moisture content.

C. Availability of moisture

Grain can contain water in several forms and the availability of water to various pests is affected by both the type of cereal and the storage temperature.

All grain contains potential water in the form of carbohydrate that can be metabolised according to the following pathway:-



During its life cycle, an insect may consume several grams of carbohydrate (WHITE and SINHA, 1981) and, therefore, produce a corresponding quantity of water. Some of this metabolic water will be retained by the insect but much will be released into the grain bulk. A heavy infestation of insects or mould can produce

water so rapidly as to increase the local moisture content of the grain (HOWE, 1962). The metabolism of insects or mould also releases heat which may set up convection currents, thus helping to transfer the moisture and concentrate it in other parts of the grain bulk. In this way an infestation of insects in dry grain can result in the production and transfer of sufficient water to allow serious mould growth and the development of a "hot spot".

Grain with a measurable moisture content contains free water molecules. The various states in which water is held in grain have been mentioned in the introduction and seem to exert little influence on the development of insects, although mites and micro-organisms require free water. The moisture content of grain in a bulk controls the rh of the air in the spaces between grains (intergranular spaces). During storage this air will take up or lose water vapour until an equilibrium is reached, giving an erh. The exact erh for a given moisture content will vary with temperature and, to a small extent, with the variety of cereal (HENDERSON, 1987a; PIXTON and HENDERSON, 1981). This is of fundamental importance to mites and mould, the development of which depends on the rh in the intergranular spaces rather than the moisture content of the grain (BANKS and DESMARCHELIER, 1978).

Moisture content/equilibrium relative humidity relationships:-

Within a mass of grain, undisturbed air in the intergranular spaces will settle to an equilibrium rh that is controlled by the moisture content and temperature of the grain. Air has limited capacity to hold water so that under normal conditions within a bulk, the amount of moisture in the grain will always far exceed that contained in the air. Therefore, the moisture content of the grain will control the rh of the air, given restricted air exchange. However, in practice, grain at the surface of bulks can come into contact with sufficient air to enable it to undergo a significant change in moisture content. Therefore, the surface of bulks can be expected to gain moisture in the winter, because of the generally high level of humidity and to lose moisture during the summer. Such exchanges of moisture during storage are

difficult to prevent or control.

The effect of temperature on the rh within a grain mass is frequently overlooked when advice is given on safe storage moisture contents. For example, assuming that an intergranular rh of 65% or less will prevent the development of mites, this rh will occur in wheat at a moisture content of about 14% at 25° C, but will require a moisture content of 15% at 5° C (HENDERSON, 1987a). Therefore, from a biological standpoint, cooling can provide the same effects as drying but at much lower costs. This phenomenon can also have a fundamental effect on the quality of grain exported from the U.K., as perceived by the customer. Grain shipped at 15% moisture and 10° C might be considered safe for continued storage once it reaches its destination. However, storage in a warmer climate could result in the intergranular rh rising to a level at which mites and mould could flourish. Such considerations must be borne in mind if the reputation of U.K. grain is not to be adversely affected.

C. Biological requirements

Moulds:-

Many species of mould can develop on grain during storage but the development of all are controlled by the temperature and moisture content of the grain. The species are reviewed by SINHA and MUIR (1973) and CHRISTENSEN and SAUER (1982), and the damage attributable to micro-organisms was considered by WILKIN and ROWLANDS (1988). Whilst moulds can cause serious damage to stored cereals, most grain is stored at moisture contents and temperatures that give intergranular values of rh below the minimum level for the development of most species (75 - 80% rh). Within the U.K. this effectively limits the damage caused by micro-organisms on stored grain.

However, at 25° C or more, storage of grain at moisture contents close to 16% must result in relative humidities within the bulk of at least 75% (HENDERSON, 1987a). Therefore, farmers

or storekeepers operating close to the maximum trading standard must run the risk of mould growth during storage, at least in the period immediately following harvest. The likelihood of problems is increased by errors in the methods of measuring moisture content, coupled with the adsorption of moisture by the surface layers during the winter. The lack of rapid methods for measuring mould growth or the production of mycotoxins may account, in part, for the continued acceptance of 16% as a trading standard.

At harvest, grain may often have a moisture content and temperature high enough to support the growth of micro-organisms. Normally, any development would be cut short by drying before storage and cooling during the first month of storage but, if bulk drying with ambient air is employed, the drying process takes several weeks to complete by which time a substantial growth of micro-organisms may have occurred. The development of fungal mycelia during slow drying will tend to restrict air-flow through the intergranular spaces and, in some circumstances can prevent the completion of drying. Technical data on the growth of micro-organisms during slow drying are lacking and more research targeted at this area would enable better management strategies to be formulated for the control of ambient air driers.

Mites:-

More than of 100 species of mites have been found in farm-stored grain in the U.K. but only about three or four species are common pests (GRIFFITHS *et al.*, 1976). All the pests require certain minimum levels of humidity in the intergranular spaces before they can develop. In the case of the two most common species, *Acarus siro* and *Glycyphagus destructor*, laboratory experiments show that they require at least 63% and 75% respectively to complete their life-cycles (CUNNINGTON, 1985; HUGHES, 1976; STRATIL *et al.*, 1980).

This moisture requirement means that mites are very often found in grain stored at or above 16% moisture content. Their ability to breed at low temperatures magnifies this problem and, as a result, mite infestations are the most common form of

infestation in U.K. grain (WILKIN and HURLOCK, 1986). Conversely, in parts of the world where grain is stored at moisture contents of below 14%, mite infestations are unknown.

Insects:-

There are tremendous variations in the conditions needed by different groups and species. For example, the Confused Flour Beetle (*Tribolium confusum*) can survive on flour containing less than 8% water (FRAENKEL and BLEWETT, 1944) although LHALOUI et al. (1988) found that the same insect needed a moisture content of 10% to complete its life-cycle on wheat. By comparison, the Hairy Fungus Beetle (*Ahasverus advena*) can only complete its life-cycle when grain moisture contents exceed 16% at 25° C (HILL, 1965). Insects that are able to live under dry conditions probably obtain much of their water needs by retaining the metabolic water produced during the oxidation of food (FRAENKEL and BLEWETT, 1944).

As stated earlier, some insects can develop on grain at very low moisture contents. Indeed, most of the common grain pests found in the U.K. can develop on grain at moisture contents of less than 14%. The minimum relative humidity requirements for some key pests were summarised by HOWE (1965) and some examples are given below:-

<i>Sitophilus granarius</i> (Grain Weevil)	50%
<i>Oryzaephilus surinamensis</i> (Saw-toothed Grain Beetle)	10%
<i>Tribolium castaneum</i> (Rust-red Flour Beetle)	1%
<i>Cryptolestes ferrugineus</i> (Rust-red Grain Beetle)	10%

Although drying, at least to levels economic in the U.K., would not appear to be an economic method of controlling insects, the rates of increase of most species are slower in dry grain. HAGSTRUM and HEID (1988) considered that moisture content of wheat was of paramount importance in controlling the rate of insect development in wheat stored in the USA. This view was confirmed by STOREY et al. (1982) who showed that the frequency and level of infestation in samples of wheat collected at US

ports, was directly related to moisture content. The level of infestation was 5 times greater in samples with a moisture content of greater than 13% than in samples below 10%. Therefore, even under U.K. conditions, reducing moisture contents may have some beneficial effects regarding insect infestation.

Effects on pesticides:-

Although the effect of moisture content on pesticides is principally chemical, it does also have important biological considerations. Insects and mites are often controlled by the admixture of a pesticide with grain. Such treatments were reviewed by WILKIN and ROWLANDS (1988) and SNELSON (1987), who concluded that they offer a low cost and effective method of preventing the development of pests in grain. A single treatment can offer protection from infestation for many months but the period of protection is affected by the moisture content and temperature of the grain. DESMARCHELIER (1976) developed a model relating the speed of degradation of several pesticides applied to grain to the moisture content and temperature. In all cases, increases in moisture content resulted in a shorter period of protection, but this was more pronounced at temperatures above 25° C.

D. Conclusions

In the U.K. the primary reason for drying grain is to prevent biodeterioration. Moisture in grain has a profound effect on the development of mites and micro-organisms. However, temperature influences the availability of moisture to the organisms and this factor is often not fully understood or considered by storers of grain or research workers.

Small variations in grain moisture content caused by problems associated with the method of measurement or sampling could be sufficient to allow mites and moulds to develop where none were expected, particularly if the production of metabolic water is taken into consideration. The converse could equally well be true, and may account for the claims such as "I have

stored grain at 16% moisture and never had a problem with mites or mould".

Much of the biological data used in this Chapter were generated using methods of determining moisture that give results differing from those produced by current methods. As a result, quoted values for "safe storage" moisture contents may need modification (see Chapter 3). In addition, much data on the moisture requirements of many of the key pests are frequently expressed as rh rather than moisture content of products that could be expected to be attacked by the pest. This, coupled with the failure to take account of the influence of temperature on the availability of water and the lack of standardised methods of determining humidity or moisture content, limits the value of the data and illustrates a clear need for more work in this field.

Chapter 3 Measurement of moisture content

The definition of moisture content, suggested in Chapter 1, implies that reliable and repeatable methods of measurement are available and are independent of the analyst. This may often prove difficult to substantiate in practice. Numerous methods have been developed for measuring moisture content. One of the earliest techniques involved the evaporation of moisture from grain immersed in a suitable heated fluid (BROWN & DUVEL, 1907). This was modified by HUGHES and GALE (1966) so that 100g of grain was heated in oil. The total mass loss is assumed to be the moisture content of the grain. It would be unreasonable, however, to expect estimation of moisture content to better than $\pm 0.5\%$ by this method even under ideal conditions.

More recently a range of methods has been developed to service the needs of farmers and grain traders. The most reliable and repeatable techniques have become known as "reference methods" but are generally tedious, lengthy and beyond the scope of many users. Accordingly, several "standard" methods have been devised upon which day-to-day grain trading have been based. Unfortunately, these are not always in agreement - different standard methods may yield different results for the same sample of grain.

Additionally, there are many "rapid" methods in everyday use, most of which rely on measuring physical or chemical properties of grain which are closely but not necessarily directly related to moisture content.

A. Reference Methods

Karl Fischer:-

This method is generally regarded as being the nearest to achieving the ideal as an "absolute" determination of moisture content. It relies on the extraction of the water from a solid by means of a suitable solvent (e.g. methanol) and subsequent titration of the extract against a Karl Fischer reagent. The extraction is made at 64.5°C , so causing minimal degradation of the grain or removal of other volatile components. The reagent is specific to water, thus obviating errors arising from the presence of oils or volatiles. The technique was discussed by HART and NEUSTADT (1957) and by JONES and BRICKENKAMP (1981) in its direct application to grain.

The method suffers from the disadvantages of complexity and expense, rendering it unsuitable for regular use. In addition, personal experience of staff at the Slough Laboratory does not confirm the reliability or accuracy of the method (ROWLANDS and HENDERSON, *ers. Comms.*) Therefore, other reference methods have been introduced. The most important of these has been made the basis of both British and ISO standards and is as follows:-

Basic Reference Method:-

The technique relies on the determination of moisture content by weight loss from a ground sample heated to 45 to 50°C at reduced pressure (1.3 to 2.6 kPa) in the presence of a desiccant (phosphorus pentoxide). The process is continued until constant mass is achieved, requiring a test period of more than 48 hours. The sample moisture content is calculated from its weight loss and its original mass. The method has been adopted as International Standard ISO 711 1978, and British Standard 4317: part 2:1980 and has been applied successfully to wheat, barley, rye, oats and some imported grains.

The length and complexity of the method renders it unsuitable for normal laboratory use, and (according to the

Standard Specification) it is "intended to serve as a method for checking and perfecting routine methods". This has led to the development and introduction of methods more suited to routine use in conventional laboratories.

B. Standard Methods.

There is a number of standard methods used throughout the world grain trade. Not all can be covered in this review but some important examples are discussed below.

Routine (oven) method:- This is the standard upon which European grain trading is now based. The brewing and the stockfeed grain suppliers may still prefer to adhere to their own established standards, but all international and intervention grain trading within the EC is based on this routine method.

Two sub-samples are taken from the batch of grain under examination, ground to a specified degree of fineness, and the weight loss of each is determined after heating in a ventilated oven at 130 to 133°C for 2 hours. The moisture content is calculated and the mean of the two values taken. If the moisture content is greater than 17% or less than 7%, a preconditioning procedure is required.

This method is referred to as British Standard 4317: Part 3: 1987 and is identical to the International Standards Organisation method ISO 712 1985. It applies to cereals other than maize. British Standard 4317:part 15: 1981 specifies procedures for the determination of moisture content of maize, both by a reference method and a routine method.

ASAE Standard:- The American Society of Agricultural Engineers has published its own recommendations which again are based on determination of water in crops by weight loss. For cereals, 15g samples of un-ground material are heated in a gravity-convection or forced-convection oven, at 130°C, for various periods of time as follows: barley 20h, oats 22h, rye 16h, wheat 19h. Average

values from two or more determinations are made. The same ASAE Standard (ASAE S352.1) specifies oven temperatures and heating times for many other crops.

U.K. Feed Trade Standard:- It has been traditional for this branch of the British grain trade to use its own standard method (Fertiliser and Feeding Stuffs (Amendment) Regulations 1976). Here, samples of milled feed grain are heated for a total of 4h at an oven temperature of 100°C. Essentially the process requires that 5g samples are dried to constant weight.

Irish Standard:- There is an "unofficial" Irish standard for cereals: a relic from pre-EEC days, which involves heating milled samples at 130°C for one hour in an oven, except where sale into Intervention is envisaged. Essentially the method is similar to that of ISO 712, except for the period of oven heating.

Institute of Brewing Standard:- This method is primarily intended for malting barley and involves the oven-heating of ground samples at 105 -107°C for 3h. STOWELL (1977) has made a comparison between the earlier version of this Standard and BS 4317, Part 3.

Despite the care taken in establishing the several standard methods listed above, it is apparent that substantially different results can be obtained, both between methods and by different operators using the same method.

Table 1 summarises the oven regimes required by the above mentioned standards.

Table 1 : Standard Methods for Moisture Determination in Grain and Seeds

Standard	Sample size (g)	Sample preparation	Oven temp. (°C)	Exposure time (h)	Grain type

ISO 712	5	Milled	130 to 133	2	Wheat and barley
BS4317 Part 3					
/					
ASAE S352	15 min	Unmilled	130	20	Barley
	100 max		130	19	Wheat
			103	72	Maize
Fertilisers and Feeding stuffs					
	-	Milled	100	4	Wheat and barley
Irish Reference					
	-	Milled	130	1	Cereals
Inst. of Brewing					
	-	Milled	100	4	Barley

C. Sources of Discrepancy Within Standard Methods.

Discrepancies within a method can arise because of different interpretations of the methodology by the user. HENDERSON & WILKIN (1985) compared results obtained by 11 different laboratories, using the BS 4317 method, with prepared samples of wheat at different moisture contents. Discrepancies of more than

0.7% moisture content between some laboratories were found. In a smaller but equally well controlled experiment, HUGHES et al. (1982) also reported differences of up to 0.4% moisture content in results obtained by different laboratories. Here the reason was firmly declared to be grinding differences.

To clarify the situation, HENDERSON (1986) conducted a trial using four size ranges of ground product. The results showed, quite convincingly, that the particle size to which the sample is ground significantly affects results by as much as 0.7% moisture content at 15% moisture.

The type of mill used is also of importance as was shown by DIMMOCK et al. (1987) who compared five commercially available machines. Discrepancies among the moisture determinations were attributed to heat generated, and consequent drying, during the milling process.

OXLEY and PIXTON (1961a) observed day-to-day variation of 0.15% in moisture content results obtained using an oven drying method, and attempted to explain them in a later study (OXLEY and PIXTON, 1961b). Variation in grinding was considered to be the largest cause but fluctuations in oven temperature, ambient humidity and barometric pressure had smaller influences.

Each standard oven method specifies a time for which the sample should be exposed in the oven. However, the rate of regain of temperature after the addition of samples is not always taken into account. BS 4317 attempts to overcome this problem by specifying that samples should be exposed for 2h at 130° C, timed from the point at which the oven regains 130° C. Unfortunately, the rate at which an oven regains temperature is not specified and is probably of equal importance.

OXLEY and PIXTON (1961a) also demonstrated the importance of drying to constant weight when using oven drying methods but this is not incorporated in commonly used standard methods.

D. Comparison of Standard Methods

Each of the standard methods described was chosen or devised because of its ability to yield consistent results. It is well known, however, that methods may not all agree with one another. BOWDEN (1984) compared the ISO 712 and ASAE S352 methods for both barley and wheat over a range of values of moisture content. In general, the ASAE (whole grain) method gave more consistent results among replicates than the ISO method. However, the S352 readings were consistently lower than the ISO results: above 17% moisture content the S352 method yielded results consistently some 0.6% to 0.8% lower than ISO. These observations appear to bear out the above comments on milling influence.

OXLEY et al. (1960) and WARNER and BROWN (1963), among other workers, also noted differences between the values of moisture content yielded by different time and oven temperature regimes. A report by the HGCA (1986) summarised the situation and pointed out the need for further work to assess differences arising from the use of various Standard Methods.

It is evident that among the various standard methods and even among users of any one method, discrepancies may be expected in results. Such differences can give rise to disputes in grain trading, emphasising the need for a unified approach to moisture evaluation.

E. Rapid methods - Direct Measurement

All of the reference and standard methods are "primary" or direct methods of moisture determination; that is, they allow direct measurement of the moisture removed from the grain. Other direct methods are available, but are often found to be less repeatable than the standard techniques. Nonetheless, they may be employed for day-to-day use in appropriate circumstances, generally because they are more rapid, and so are described here:

Infra-Red Heating:-

A ground sample of some 5g to 10g of the grain under test is weighed and exposed to the radiation from an infra-red lamp of about 250W. After a period of time which depends upon the distance from the lamp to the grain, the grain is re-weighed and the moisture content calculated from the weight loss. This method can yield consistent results if the grain is exposed uniformly to the radiation, not overheated (burned) and sufficient exposure (10 to 20 minutes) is used.

Some commercially available versions of this type of apparatus provide for continuous counterbalancing of the sample under test so that its weight loss is indicated directly. The constant weight condition is easy to identify under these circumstances and the moisture content can be read off immediately. Some disagreement among investigators (STEVENS and HUGHES, 1966; WARNER and HARRIES, 1956) has been attributed to differences in fineness of milling of test samples, although variations in supply voltage were also suspected. STEVENS and HUGHES found discrepancies up to 0.7% m.c. (wet basis) arising from these causes.

Rapid Oven Method:-

An accelerated oven test, once greatly favoured in the grain trade but now little used, employed a Carter Simon Oven which was limited to three sample tins only. Weighed, replicate 5g samples of ground grain, contained in these 50mm diameter tins, were heated at 155^o C for 15 minutes and re-weighed. Users claimed that repeatability to within 0.2% m.c. was attainable and STEVENS and HUGHES (1966) quoted a standard deviation of 0.11% for a single determination. The Carter Simon Oven is no longer available commercially and few examples of its regular use are known. However, in the hands of an experienced worker it could probably be relied on to be as reliable as most current moisture meters.

A similar oven regime is employed by exponents of the Brabender oven method. Again this equipment is infrequently encountered nowadays, but it has been claimed to offer superior accuracy because, as a self-contained unit (which can contain up to ten samples at a time) the method avoids errors which can occur when samples are transferred from oven to desiccator to balance. The method has been used for moisture determination of grain in West German Intervention Stores.

A little-used technique which has received some attention and which may be exploited increasingly once its reliability has been established, is the removal of moisture by microwave heating. VERMA and NOOMHORN (1983) explored the use of a domestic microwave oven for the purpose with some success particularly at higher values of m.c.

Chemical Methods:-

A simple method based on the chemical reaction between calcium carbide and the moisture in ground cereal grains has been in use for more than 25 years. The reacting materials and the gas (mainly acetylene) which is evolved, are held in a sealed container and the pressure of the gas gives an indication of the moisture involved in the reaction. The method has now been displaced by modern techniques.

F. Secondary or Indirect Methods

Most rapid measurements of moisture content in grain rely on quantitative determination of some physical property of the grain which is directly related to water content and from which the moisture content can be inferred. The best known of these are the electrical properties, in particular the conductivity and the dielectric constant of the material. The principles and practice of these measurements and others based on determination of magnetic, optical, vapour pressure, acoustic and other properties are now discussed.

Electrical Conductivity:-

The ability of grain to conduct electricity is closely related to its moisture content. This was recognised by BRIGGS (1908) and has given rise to the introduction of a wide range of moisture meters which are based on the measurement of electrical resistance (or its reciprocal, conductance). Many of these instruments have gained a high reputation for accuracy when assaying cereals and other seeds and they have a recognised place in the grain industry.

However, resistance moisture meters suffer from one significant disadvantage as far as the user is concerned: it is necessary for the grain to be milled to obtain accurate results. The milling enables a good and repeatable electrical contact to be made between the grain and the measuring electrodes. In most instruments this contact is enhanced by the application of a compressive force to the surface of the grain, ensuring that as much air as possible is driven from the interstices of the milled particles. A repeatable degree of compaction is usually applied by means of a suitable spring-loaded clamp or torsional compressor.

The electrical resistance of a grain sample is influenced by the temperature of the material under test. It is necessary, therefore, that some means of compensating for variations in temperature are provided. This may be in the form of a numerical correction applied by the operator when he has measured the grain temperature or a correction applied automatically by an electrical circuit of the instrument. In the latter case, the grain temperature is determined by an electrical thermometer (usually a thermistor) embedded in the sample cell so that it makes good thermal contact with the grain. Most instruments are calibrated at a grain temperature of 20°C and corrections are applied for any deviation from this. A temperature change of $+10^{\circ}\text{C}$ usually requires a correction of about -1% moisture content to the indicated meter reading. It should be emphasised that the important temperature is that of the grain, not that of the air.

The electrical conductivity meter can be used with whole grain, but with less confidence than when the grain has been milled. Whole grains offer poorer electrical contact between themselves and the electrodes, the temperature of the grain may not be determined with such accuracy, and any internal moisture gradients within each grain, which may have arisen from recent drying or wetting of the grain, has a substantial effect on the reliability of the measurements.

ZELENY (1954) pointed out that the highly non-linear relationship between grain moisture content and its electrical conductivity limited the usefulness of these instruments to the range 7% - 23% moisture content. This remark is only applicable to non-oilseeds. For oily crops, the range depends greatly on the oil content of the material, but for oilseed rape of about 43% oil content, one conductance meter was unable to give reliable readings above 17% m.c. (STENNING and ASHBURNER, 1980). It should be pointed out, however, that at least one other commercially available instrument, perhaps as the result of careful cell design, is able to read beyond 20% before losing sensitivity (MEHARI, 1988). This instrument is also capable of dealing with cereals of moisture content at least to 28% m.c.

The electrical measurement of conductance (or resistance) is usually made by means of a direct current (d.c.) circuit often based on the Wheatstone Bridge. Some operators have questioned the advisability of use of d.c. (HUKILL, 1957), being concerned about errors which might arise from polarisation of the test material. There is, however, little evidence of this problem if instruments are used according to the manufacturers' instructions.

A criticism sometimes levelled at most designs of conductance - based instruments is the small amount of sample (5g to 10g) which they can accommodate. Certainly great care must be taken in the sampling procedure if truly representative readings are to be obtained. Manufacturers make this clear to users, but accurate sampling is a time consuming activity and

users may be deterred by the necessary procedures. Some capacitance based instruments often require as much as 300g of grain and may thus be thought to give more representative readings. There is little evidence, however, that they give more reliable readings than their conductance counterparts, and for rapid use in the field, in assessing the moisture content of standing corn, the "rubbing out" of 300g of grain (approximately three quarters of a pint) is a tedious matter.

At least one attempt has been made in the past to measure the moisture content of bulk stored grain *in situ*, as opposed to the more usual procedure of collecting representative samples and making the assay by portable meter or standard method. GOUGH (1980) reports the use of sensors which were distributed throughout beds of stored grain. These sensors relied on measurement of the electrical conductivity of a small quantity of grain contained between conducting electrodes. The grains were allowed to come to equilibrium with the bulk of stored material and their moisture content was then inferred from the measured conductance. The reported robustness and sensitivity of these sensors when exposed to relative humidities of less than about 70% has led to their use in a number of research situations. There is little evidence, however, of their use in commercial grain stores: presumably the inconvenience of installation and regular monitoring has overshadowed any operational or economic advantages.

Another device (HUKILL, 1957) relied on the equilibrium moisture content which was assumed by the cotton fibre of simple pipe cleaners when these were embedded in stored grain. Again, the measurement of electrical conductance gave a guide to the grain moisture level, but in this case a notable lack of repeatability limited the application of the devices to detection of moisture gradients rather than actual moisture levels.

Dielectric Constant:-

ZELENY (1954) recognised that the dielectric constant of grain increases sharply with moisture content. It is also dependent

on the frequency of the alternating current used in the measuring circuit, but, for frequencies up to about 1MHz, varies from a value of about 4 for dry grain up to about 80 for pure water. Dielectric constant is measured by placing a sample of the moist material between two conducting plates forming a "capacitor" or "condenser". The "capacitance" of this unit is, therefore, related directly to moisture content and this has been widely exploited in the design of capacitance moisture meters.

Two advantages of this type of instrument are that it allows measurements to be made on whole grain and that, relative to conductance instruments, large samples of grain (typically 30g to 300g) are assayed. However, the advantages are somewhat offset by the sensitivity of the instrument to the packing density of the material in the cell, i.e. the ratio of moist grain to interstitial air. The density varies from sample to sample so that some means of compensation or correction for this variable is required (MCFARLANE, 1987). As with the conductance method, capacitance measurement is also temperature sensitive, imposing the need for compensation here too.

A continuing programme of research into the use of grain dielectric properties for the estimation of moisture content has been undertaken by Nelson and colleagues, leading to a range of publications on the subject. Dielectric constant varies inversely with frequency (NELSON, 1965), but almost linearly with temperature (NELSON, 1982) exhibiting a positive temperature coefficient. Bulk density was included as a correction factor in an analysis of winter barley (NELSON, 1986). Some early workers claimed that the dielectric constant of a grain sample was independent of moisture gradients within individual berries (as may have arisen from recent wetting or drying of the grain). SOKHANSANJ and NELSON (1987) have disproved this hypothesis, showing that an equilibration period of some two to six hours was required after substantial changes in moisture content had been induced. Measurements made at a supply frequency of 1GHz were much less susceptible to moisture gradient than measurements made at 1, 18 and 300 MHz. It is worth noting, however, that most of the commercial moisture meters which use dielectric measurement

operate at frequencies of 5MHz or below, where sensitivity to gradient may be important.

A large range of moisture meters utilising the capacitance principle has been developed world-wide. The principle is widely favoured for the assay of both agricultural commodities and other products such as paper, powders, etc. The limitations of the technique, as investigated by Nelson and others, have been minimised by careful design. However, the operator of a portable grain moisture meter is still an important contributor to the overall accuracy of the method. STENNING and CHANNA (1987), investigated many causes of error in capacitance moisture meters and were able to quantify some of the likely discrepancies or disturbances arising from variations in the physical and non-physical characteristics of the grain. These, together with results obtained by DWYER et al. (1980), are summarised in Table 2.

Table 2: Causes of inaccuracy in capacitance moisture meters (DWYER et al., 1980; STENNING and CHANNA, 1987)

Grain	Apparent cause	Magnitude (% Moisture)
Wheat	Variety	+/- 0.75
Wheat	Repeated wetting and re-drying	1.0
Spring wheat	Year to year differences	2.0
Barley	Year to year differences	1.5
Barley	Awns and impurities	1.5

A small number of very recent bench-based instruments require little or no action by the operator apart from placing the sample to be assayed into a receiving hopper. Thereafter, loading of the measuring cell and all subsequent determinations of mass, density, temperature and electrical characteristics are made without user intervention. Such instruments are potentially the most accurate of their kind, but still they may be susceptible to the variations in grain characteristics mentioned in Table 2.

LAZARO (1986) investigated the effects of sprouting of grain on the calibration of conductance and capacitance based moisture meters. Both types showed susceptibility to the degree of sprouting, suggesting that some change in the electrical characteristics of the grain had occurred. Errors up to +1.5% m.c. were found with grain which had been sprouted for 24 hours on the laboratory bench. MBOGE (1987) continued the work, but was unable to repeat the effect upon capacitance instruments for sprouting periods less than 24 hours.

Nuclear Magnetic Resonance (NMR):-

The atomic nuclei of many elements behave, under certain conditions, as though they are spinning bar magnets. Each may be likened to a spinning top, which is precessing about a vertical axis. When the nucleus is subject to a strong, constant magnetic field, the frequency with which it precesses is characteristic of the element.

Hydrogen, in a water molecule, i.e. as moisture in cereal grains, has its characteristic frequency and can be identified. The quantity of hydrogen present can also be evaluated and, provided that the situation is not confused by the presence of hydrogen in similar form (e.g. as a component of oil in oilseeds), the moisture content of the seed can be evaluated.

Use of this technique is in its early stages as a means of measuring grain moisture content, but notable success was achieved by MORLEY et al. (1984) in calibrating NMR measurements

against oven determinations. Correlation coefficients better than 0.999 were obtained, suggesting that the technique is well worthy of future investigation (see Chapter 7). Pulsed NMR had earlier been explored by MILLER and LEE (1980) with some success for grain in the range 15-40% moisture content.

To date there are no purpose-built moisture meters on the market which employ NMR principles. Indeed the existing laboratory equipment is very expensive and essentially not portable. However, it is to be expected that the potential accuracy of the method will lead to efforts by manufacturers to introduce purpose-designed instruments for agriculture.

Near Infra Red (NIR):-

The estimation of moisture content by optical means has a number of attractions. Light energy of specified wavelengths can be readily generated; detectors are available, which are sensitive to a wide range of wavelengths; the selection of light of specific wavelengths is easily achieved by means of filters. Unfortunately, light in the visible waveband (400 - 700 nm) is not useful in the specific detection of water, but in the Near Infra Red region, at wavelengths of 1450, 1940 and 2950 nm there are strong "absorption bands". By selecting one or more of these wavelengths and measuring the extent to which the light is absorbed by the moist material under test, an estimate can be made directly of the amount of water present (BEECH and BENSON, 1988; DOWNEY, 1985). The absorption is measured by implication, i.e. it is really the reflected radiation which is measured, giving rise to the acronym NIR (near infra red reflectance), by which the technique is usually known.

Existing commercial instruments, mainly based on the use of filament lamps as sources of radiation and requiring filters for the selection of the specified wavelengths, are in regular use in industry for such purposes as on-line measurement of moisture content of webs (e.g. paper) and powders.

Unfortunately the technique is not entirely suitable for the assay of moisture in whole grains because the depth of penetration of the radiation into the surface is small. However, instruments for use in agriculture are in the process of development (see Chapter 7), with particular application to small particle or thin film (e.g. grass) measurement and can be expected to find a place in the industry in the near future.

Microwave Attenuation:-

Electromagnetic (radio) waves of certain frequencies are absorbed by grain to an extent dependent upon the moisture content. The technique is not used commercially, except in a small number of on-line control processes and is otherwise still at the research stage (see Chapter 7).

Relative Humidity/Percentage Saturation/Water Activity:-

The equilibrium relationship between the moisture content of stored grain and the relative humidity of the interstitial air can be measured and used to calculate the moisture content of grain. However, the results are affected by temperature.

Hair hygrometers have been popular as instruments to determine the relative humidity within a bulk of grain. However, this type of instrument suffers from a number of imperfections which limit its usefulness, although it is one of the few methods available for in-situ estimation of the moisture content of bulk grain.

GOUGH (1976) preferred to extract samples of the interstitial air by means of a pump and determine its relative humidity by means of an appropriate instrument. For grain samples of known moisture content, good agreement was obtained between expected and measured values of relative humidity, suggesting that the method was worthy of further investigation. It is noticeable, however, that it has not been pursued in practice. Indeed, it may be said that there is no widely recognised method of measuring moisture content of bulk grain

except by the removal of representative samples (see Chapter 6).

PIXTON and EMERSON (1963) used cobalt thiocyanate paper as an indication of interstitial relative humidity and, hence, grain moisture content. The method has not been used widely and the toxic nature of the chemical must render its use inadvisable in a food context.

Acoustic Methods:-

Audio techniques are currently the subject of research (FRIESEN et al., 1988), - see Chapter 7.

Other Techniques:-

In the past a wide range of techniques for measuring moisture content has been proposed but most have proved unsatisfactory for a variety of reasons, often related to the variability of the grain under test from season to season (weather and growing conditions), day to day (possible chemical/biochemical changes), or place to place (different storage conditions).

Measurement of the surface friction of grain has been examined as a possible guide to moisture content and is, perhaps, worthy of particular note here because it is the basis of the most obvious of all subjective tests, i.e. the "feel" of the grain. The angle of repose of a heap of grain has been used by some workers as a quantitative indicator of moisture content. In an attempt to adapt this idea to a workable and repeatable instrument, FINN-KELCEY and CLAYTON (1955) examined the depth of penetration of a heavy, sharpened blade into a pre-compacted bed of grain. At the laboratory stage, good correlation was found, but problems were later recognised as arising from variations in cereal variety, the history of the grain (i.e. drying and wetting since harvest) and a range of other factors. The instrument was

never developed, for these reasons.

G. Calibration and Operation of Moisture Meters

In the experience of the authors, most manufacturers of moisture meters adopt a highly responsible attitude to the calibration of their instruments. Many have their own laboratories, in which regular calibration checks are made on a wide range of species and varieties of grains. Attention is also paid to the occurrence of year to year changes in the properties of the grain. In general, also, the larger manufacturers are prepared to investigate calibration deviations which may be experienced by users when occasional rogue batches of grain are encountered. Unfortunately, some instruments are sold with little or no technical support and very limited data as to the standard against which the meter was calibrated.

Where there is need for a manufacturer's data to be confirmed, he may call on the services of an independent laboratory. It is interesting to note, however, that at present there is no national organisation in the U.K. which takes responsibility for testing new or modified instruments which may appear on the market. STEVENS and HUGHES (1966) made a technical comparison of instruments available at that time, but no more recent comparison is available to guide prospective purchasers. Nowadays testing is mainly the responsibility of the manufacturer or user. From time to time a comparison of a limited range of instruments may be made, perhaps by a publisher on behalf of his readers (ANON, 1986; HORBURY, 1987), or by an independent laboratory at the request of MAFF (STENNING & WARD, 1985), but there are no routine evaluations. There is an ISO method for checking the calibration of moisture meters. However, this has not been adopted by the BSI. A procedure similar to the ISO method is described by GOUGH (1983).

The procedure used for calibration involves the careful preparation of batches of grain at a number of different moisture contents covering the required range. This is achieved by the addition of calculated quantities of water to the grain, sealing

the mixture in a non-absorbent container (e.g. a Kilner Jar) and agitating it at regular intervals over a period of at least three days. A seven day period is preferred by some authorities. The sample containers are kept at either room temperature (for the shorter period) or about 4° C (for the seven days) to ensure thorough diffusion of the water through the grain. A method for moistening samples, as required by the French authorities, has been defined in ISO 7700/1 and applies to small grains such as wheat and barley. Where dry samples are required, natural drying of the parent material at laboratory temperature is employed. Warm air drying at some 40° C is a possible alternative, if followed by a two day equilibration period in a sealed jar. However, it has been suggested by some authorities that correct calibration will only result from the use of "natural" samples that have not been wetted or dried. This appears to be particularly important in the case of maize, where added water "is never distributed in the same way as naturally occurring water" (MARTIN and MULTON, 1988).

In re-calibrating a moisture meter, the user must follow the manufacturer's instructions with care. The apparent value of the moisture content of a series of test samples is determined, both by the meter and by one of the Standard oven methods already described, so that appropriate statistical analysis may be made and confidence limits assigned to the results obtained. LEFKOVITCH and PIXTON (1967) described a relationship between a meter and a standard oven method that they obtained by regression analysis.

The occurrence of slight inconsistencies in the results from standard oven methods has been described above and must add to the difficulties of calibration. Greater discrepancies between portable moisture meters may occur, particularly in the case of instruments which do not incorporate some form of controlled loading or compression system. Variations in the detailed physical dimensions or electrical circuit characteristics between ostensibly identical models of moisture meter are also responsible for calibration discrepancies, emphasising the need for regular servicing of moisture meters. Generally, users of

moisture meters must accept that their instruments will give a good guide to the moisture content of a sample but that there are many factors that will affect the precision of the results that they obtain. Therefore, too much emphasis should not be placed on the reading obtained, particularly if it is based on a single determination of a single sample.

H. On-Line Measurement of Moisture Content

At present there is little use made in agriculture of on-line moisture measurement during either drying or processing of grain. Where automatic moisture control is employed, predominantly in continuous flow or batch grain driers, the moisture content is usually inferred from measurement of the exhaust air temperature.

A small range of on-line moisture meters, based on either conductance or capacitance measurement, exists and some current research and development is taking place in this area. It is to be expected that new on-line moisture sensors will become available in the near future. Once the problem of on-line measurement has been satisfactorily solved, the development of a new generation of automatic moisture control systems can be expected to follow.

I. Observations by Manufacturers and Agents

A letter of enquiry was sent by the authors to 22 manufacturers of moisture meters or their agents in U.K., Europe and U.S.A. Only five replies were received: the comments and observations of those who replied bore many similarities. All were concerned about the variability of results obtained by standard oven methods. The difficulty of knowing whether or not a grain sample required preconditioning (i.e. if it were above 17% or below 7% m.c.) was of concern, as was the uncertainty of errors introduced by grinding, even if BS 4317 Part 3 was closely followed.

One respondent made reference to differences of opinion between buyer and seller which sometimes require the intervention of a third party: " Any buyer knows that if he has to go to

arbitration, all he has to do is send four or five samples to independent laboratories and he can choose the results which best match his needs- without being unfair."

General concern was expressed about capacitance based instruments which do not control, or in some way take account of, the packing density or the mass of grain in the measuring cell. The influence of "green" grains and of non uniformly distributed moisture within grains was also a matter felt to have been inadequately researched.

Finally, respondents were concerned at the lack of awareness among instrument users of the inherent variability of the natural product (grain) which was being assayed. A somewhat naive and unconsidered acceptance of instrument readings was apparent in the grain trade in spite of efforts by MAFF, journals and manufacturers to bring about an understanding of the problems of accurate measurement. Sampling errors were referred to, as were seasonal variations in grain characteristics. Two respondents referred to the recently introduced Danish system whereby one agreed type of moisture meter has been supplied to users throughout the country (ROBINSON, 1988). Each instrument is connected by telephone to a central Testing Institute from which regularly updated calibration data can be transmitted throughout the season. This ensures a common, National basis for the assay of regionally produced grain. The scheme was thought to be worthy of further examination, although the diversity of growing conditions in the U.K., as compared to Denmark, might limit its usefulness.

Thanks are due to those companies which responded:

Fyfe Electronics, High Wycombe.
Foss Electric (UK) Ltd., York.
Nickerson Bros Ltd., Lincoln.
Protimeter plc, Marlow.
Sinar Technology, Weybridge

J. Conclusions.

The accurate determination of moisture content in grain is still an elusive goal. Steady progress has been made, particularly since the 1950's when the widespread adoption of new harvesting and storage techniques required attention to be paid to grain quality. However, the principles upon which currently available moisture meters are based have been under investigation for decades and it is unlikely that any possibility of a marked improvement in their accuracy or precision has been overlooked. It seems, therefore, that until some new principle of moisture measurement is discovered or adopted, there will be no "quantum" leap forward in moisture assay. The most promising among the known, but little explored, techniques for moisture measurement would seem to be some form of nuclear magnetic resonance.

In the meantime it is important that an increase in awareness among users is encouraged. It must be emphasised that all scientific measurements are subject to inaccuracies. No measurement can compensate for sampling errors. Moisture meters are not all-embracing or universally tolerant of misuse. They require calibration, and this implies the need for a "standard" method as a basis of comparison.

Even if the above suggestions are followed, immunity from error cannot be guaranteed but it should be borne in mind that the user is always potentially the greatest source of error.

Chapter 4 Practical implications

The amount of moisture in grain has probably always been of some commercial importance when marketing grain. However, it was the change from bagged to bulk grain, which occurred during the '40s and '50s, that emphasised the need to adjust moisture content during storage. This change to bulk grain coincided with, or was caused by the change in harvesting methods. Combine harvesters, which threshed the grain in the field, superseded reaper-binders and rick storage of un-threshed crop. Combine harvesting encouraged the transition from bags to bulk and it soon became apparent that, under conditions that prevailed at harvest time in the U.K., bulk grain was often too moist to store without serious risk of biodeterioration. As a result drying systems became common thus offering the option of adjusting moisture contents to any required level.

There are no historical reviews of the U.K. grain trade that pin-point developments in the industry. FINN-KELCEY and CLAYTON (1955) referred to grain drying and recommended a moisture content of 14% for long-term storage of wheat but did not comment on any commercial implications. At some stage in the 50s or early 60s, it seems likely that moisture contents used for commercial trading were set at 16%; a level that minimised the amount of drying needed but which is marginal for safe storage. This was generally not regarded as an exclusive limit and grain would often be accepted at higher moisture contents, but with some downward adjustment of the price. This trading limit remained as the principal one in operation until the mid 1970s when the intervention regulations were introduced. However, malting barley was often stored, and presumably traded, at much lower levels of moisture, in the region of 13%. This did not seem to be enforced as a trading standard but was used principally as a method of protecting a valuable commodity during storage (BURGES *et al.*, 1963).

The traditional maximum of 16% moisture in grain is still widely used in the U.K. and forms the basis of GAFTA and UKASTA contracts. As a result, the majority of U.K. grain is traded to this standard. However, an increasing number of exceptions are being adopted by different sections of the grain industry. In 1973 when the U.K. joined the EEC, the Ministry of Agriculture, Fisheries and Food set a moisture level for grain offered into intervention that lay within the range of 14 to 16%, permitted by the Commission. A compromise level of 15% was chosen on the basis of being the highest practical value commensurate with long-term storage. The intervention system also introduced two new principles to the grain industry relating to moisture:-

i) the offerer was compensated if grain was below the maximum level and

ii) grain above 15% was rejected without any option of negotiating a lower price.

This new standard had little impact on the U.K. grain industry until the late 1970s when appreciable quantities of grain were sold into intervention storage. However, during the first years of operation, excess moisture was the most common reason for grain being rejected at Intervention stores (ANON, 1985a). This was due, in part, to the ISO method of measurement used by IBAP which gave different results from the method then in use in the U.K. (see Chapter 3) but the grain trade's lack of experience of working to maximum limits for moisture also played a large part.

As sale of grain into intervention began to exert a greater influence on the U.K. grain industry, both the need to meet maximum standards and the influence of the new methods of measurement became more widely appreciated. Data on the effects of methodology on results began to be published in the trade press (ANON, 1985b). At the same time the need to meet export standards also began to play an important part in trading U.K. grain. The intervention specification for moisture has not remained constant; in 1984 it was reduced to 14.5% but in 1987 -

8, as a temporary measure, the level was raised to 15.5% to compensate for wet harvest conditions.

The moisture content of grain has numerous financial implications for producers, storers and users, not all of which are immediately obvious. Drying costs usually form a major part of the costs of storage, both in terms of the variable operating costs of drying systems and of the fixed costs of drier installations. In most cases, large producers have their own drying facilities, often high temperature, continuous flow driers. Alternatively or in addition, bulk driers using near ambient air, may be incorporated as part of bin or bulk storage. The former method gives rapid drying without regard to ambient conditions and requires only a fairly simple management strategy. However, both capital and running costs are high. The efficient or automated operation of high temperature driers is currently handicapped by deficiencies in equipment to monitor moisture during the drying process (see Chapters 3 & 6). Bulk driers are less expensive to instal and run, but require a high level of management and are limited in their ability to deal with grain at moistures above about 19% or operate in warm, wet conditions. However, new developments in the field of dehumidifiers and control systems may make the technique more widely applicable (COUSINS and ROBERTS, 1988).

It is very difficult to give definitive operating costs for grain drying as these will be affected by:-

- i) tonnage of grain dried
- ii) amount of moisture removed
- iii) cost of finance and write off period
- iv) prevailing energy costs
- v) efficiency of system

Comparable costs for extracting water from grain based on the running costs of continuous or bulk driers are about 60p and £2.00 p/tonne/% moisture respectively. These figures take no account of costs defined in (i), (ii) and (iii) above and, therefore, the actual costs will vary substantially between users. However, these

figures show that, if grain is harvested at 18%, the minimum costs will be between £1.60 and £4.00/tonne to dry to a level below the maximum trading level. It will cost a further 90p to £1.50/tonne to dry to a level acceptable by IBAP or some flour millers and to ensure safe long-term storage. In addition the cost of purchase and maintenance of drying equipment has to be borne. On farms, this equipment stands idle for most of the year yet must have sufficient capacity to deal with maximum size of harvest under the worst harvest conditions.

Perhaps the most important benefit from drying to a moisture content below the current maximum of 16%, comes from the ability to store dry grain for long periods without biodeterioration or loss of germination. This is recognised with high value cereals such as malting barley where loss of germination during storage would have a major influence on the value of the crop (BURGES et al., 1963).

The full financial implication of all maximum moisture levels must be considered in the light of methods of measurement. These are reviewed in detail in Chapter 3 where it is suggested that there is some margin of error inherent in all methods of measurement currently in use. At a farm level, moisture is usually determined by means of an electrical meter that is unlikely to be more accurate than $\pm 0.5\%$ moisture in the range covering most trading levels. Given this standard of accuracy, it is unlikely that a farmer could succeed in drying grain to the exact maximum level specified in a contract. Even oven moisture methods, as used by the trade and the IBAP, involve some errors (HENDERSON and WILKIN, 1985). These errors and discrepancies can work in a cumulative manner so that it is possible for a merchant to record a markedly different moisture content from the farmer. There is no easy solution to this situation but some possible long-term measures that could be undertaken are discussed in Chapter 7. Workers investigating methods of moisture determination and the proposers of new "standards", should always make some estimate of the financial implications of new "improved" methods and be aware of who is likely to have to bear any financial penalties.

Chapter 5 Influence of sampling

In earlier Chapters the significance of moisture in commercial transactions and its effects on biodeterioration have been stressed. Despite this key role, numerous problems still exist regarding the accurate and reliable determination of moisture in cereal grains. Such problems in measurement obviously must create major difficulties for storers and traders of grain, yet the collection of samples for determination of moisture content probably represents a far greater potential source of error.

Immediately after harvest and drying, it is very unlikely that any bulk of grain of more than a few tonnes will have a uniform moisture content. There will have been variations in the moisture content of the grain in the field and in the performance of the drier. Obviously the operator of the drier will have attempted to compensate for these variations but is unlikely to have been completely successful. There are few data to show the variation of moisture in bulks of freshly dried grain but work by BURRELL and HAVERS (1976) showed a large variation between samples taken from a 20 tonne bulk. Thus variation between samples from a bulk may be much greater than the maximum error in any current method of measurement.

Variation in moisture within a bulk will tend to reduce with time. Moisture moves between grains, tending to arrive at an equilibrium. This equilibration occurs slowly and will never be complete even when the individual grains at different moisture contents are mixed intimately (HENDERSON, 1987b). It will be even slower and less complete if damper or drier patches take the form of lots of 20 tonnes or so within the main bulk. Hence some variation in the moisture content of particular sections of a bulk is likely to remain even after long term storage.

In addition to this inherent variation in moisture within a bulk, moisture migration may occur during storage which

increases rather than reduces differences. For example, the temperature of the grain is unlikely to be constant and this often results in air being moved through the intergranular spaces by convection. This air will also carry moisture from warmer to cooler parts of the bulk. Generally, moisture is moved up from the lower parts of the bulk and condenses on or is absorbed by grain at the surface. Such moisture migration can increase the moisture content of the surface layers of a bulk by 4% or more and this can often trigger a cycle of biodeterioration leading to major losses. However, even small movements of moisture will lead to a variation that could cause contractual problems for the seller.

The surface layers of grain are exposed to the atmosphere and will change in moisture content according to the ambient relative humidity so will tend to absorb moisture in the winter and lose water in the summer. Unfortunately, samples are often collected from the surface of a grain bulk so that, although the surface layers may only represent a small part of the bulk, the moisture content of the layer may be used to estimate that of the rest of the grain. This can lead to serious errors which usually take the form of sellers over estimating the moisture content of grain.

Bulk drying systems move air, with a relative humidity less than that with which the grain is in equilibrium, up through the bulk, drying from the bottom upwards. Therefore, during drying the lower part of the grain will be drier than the part above the drying front. One consequence of drying in bulk is that it may be very difficult or even impossible to move the drying front right through to the surface, introducing large variations in moisture content. Bad management of bulk drying systems will further exaggerate these differences by over-drying grain at the bottom of the bulk whilst under-drying the surface layers (NELLIST, 1988).

These examples of variation in moisture content of grain illustrate the importance of taking sufficient samples to give a reliable estimate of the moisture content of the whole bulk.

Variation will be greatest with changes in depth, although with large bulks some lateral variation must also be expected. Maximum variation is likely to occur between the surface 10cm and the rest of the bulk. Therefore, samples should be taken from below the surface 10cm as these will be more representative of the moisture content of the whole bulk. An estimate of the variation of moisture content within a bulk can be obtained by collecting samples from several points and examining them individually. Alternatively, all samples can be bulked and mixed before examination, so giving a better estimate of the average moisture content. One serious error that can occur with this approach is that if a sample from a particularly wet or dry part of the bulk is included this may exert an unrepresentative influence on the results. This problem can be overcome by collecting a large number of samples so that the influence of any outliers is minimised.

Clear guidelines on sampling bulk grain are hard to find in the technical literature, which is surprising as sampling can influence the determination of all aspects of grain quality. GAFTA regulations stipulate some parameters that need to be met when collecting quality assessment samples from bulk grain and the intervention regulations also provide some guidelines. However, neither of the above provide a sufficiently well defined system so as to overcome the sampling problem associated with the determination of moisture content of grain. Both the Canadian Grain Commission and the United States Department of Agriculture, Federal Grain Inspection Service, have grain sampling manuals based on past experience and confirmed by research. The lack of research on sampling in Europe and particularly in the U.K., could seriously hamper progress towards better methods of measuring moisture content and other quality factors. This problem was highlighted by WILKIN and WRIGHT (1983) but only limited progress has been made towards meeting their recommendations for more, international research. There are British Standards for collecting samples of grain (BS 4510, 1986[ISO 950]; BS 6298, 1982 [ISO 6644]). However, BS 4510 is biased towards sampling lorries rather than grain in bulk and BS 6298 covers automatic, mechanical samplers.

In the light of the above it is surprising that sampling problems associated with the measurement of moisture in grain seem to be overlooked both by buyers and sellers, and by research workers operating in the field of moisture measurement. The paucity of published data on grain sampling and its effects on the determination of grain quality would seem to support the authors' view that more work is justified to investigate moisture variation within bulks of stored grain and to develop a suitable sampling regime to provide an accurate and reliable sample for moisture determination. As a result of such work it should be possible to devise a simple statistical test that would enable buyers and sellers to estimate the variation within a bulk and to decide if sufficient individual samples had been taken.

Chapter 6 Recent research into techniques for moisture measurement

A. Background

As described in Chapter 3, the measurement techniques used in currently available moisture sensors include electrical resistance, electrical capacitance (including sampled/on-line sensors), microwave absorption and weight loss by drying methods (conventional and microwave oven-drying and infrared lamp). Grain moisture content may also be determined by laboratory type near infrared analysers. Sample preparation may be necessary and some instruments suffer from problems of long term drift, calibration stability and sensitivity to the way in which the grain is presented to the sensor. Bulk density, grain size and the presence of foreign material such as chaff or grit in uncleaned grain reduce the accuracy of such moisture meters. The problem of varying bulk density is most apparent where measurement of moisture in flowing grain is required, such as for a grain drier controller.

The above shortcomings have motivated further research and development into alternative techniques for measuring moisture content with perhaps most emphasis being placed on dynamic measurement of moisture in flowing grain situations. In assessing any new technique, it is necessary to consider carefully the reference method used. Although oven drying methods, described in Chapter 3, are frequently used, they are not strictly "reference" methods. Oven drying as a method has to be undertaken with great care to achieve accuracies to tenths of a per cent.

This chapter reviews recent and currently active research into techniques for moisture measurement.

B. Recent Research Studies

Capacitative Methods:-

It is necessary to compensate for the large effect of bulk density variation on dielectric constant experienced in a grain drier. The effects of moisture and density on dielectric constant vary with excitation frequency as shown by NELSON (1986) who derived models for dielectric constant of winter barley. In principle, it is possible to compensate for density by measuring dielectric constant (by a capacitative type sensor) at two frequencies and deducing simultaneous equations involving moisture content, bulk density and dielectric constant. The equations can then be solved to determine moisture content from dielectric constant independently of bulk density. MCFARLANE (1987) has investigated this method over a moisture range of 14.7% to 19.5% (wet basis), 68-79 kg/hl bulk density and 0.1 to 13 Mhz frequency. From his measurements he concluded that it would be possible to obtain an accuracy of 0.6% moisture content. The method is currently being further evaluated over a wider range of moisture content and density at AFRC Institute of Engineering Research.

KANDALA et al. (1987) developed a capacitative method for measuring the moisture content of a single kernel of corn. Measurement accuracy of $\pm 1\%$ was achieved.

Microwave Methods:-

The attenuation of microwave energy as it passes through a medium such as grain depends on the dielectric constant and thus on the moisture content of the medium. The particular advantage of the microwave technique is that it is non-contact and can be used for continuous measurement on flowing grain. However, in its typical implementation in waveguide form, it is an expensive system. BOWMAN (1980) has examined the feasibility of using a microwave stripline. In this configuration, microwave energy is fed into one end of a thin conductor laid on dielectric material over a ground plane. Attenuation of microwave energy along the

conducting strip depends on the dielectric constant of the surrounding medium i.e. the grain. In its simplest form, a stripline can be a single copper track on a piece of double-sided printed circuit board and thus is inexpensive. BOWMAN (1980) demonstrated the potential of the stripline technique for measuring moisture content of static samples of grain. However, as the dielectric constant is significantly affected by bulk density, the technique is not immediately applicable to varying grain density conditions i.e. flowing grain.

MARIS (1988) has developed a microwave technique at the Flour Milling and Baking Research Association for monitoring the moisture content of whole grain during conditioning at the intake to a mill. The equipment uses a commercial microwave attenuation monitor and waveguide equipment to convey the microwave energy to a perspex cell containing static grain.

The effect of bulk density variation can be offset by measuring both attenuation and phase change in microwave transmission as described by MEYER and SCHILZ (1980). The practical use of this technique has been described by KLEIN (1988) as applied to continuous measurement of moisture content of bulk materials such as coal, sugar beet chips, potato chips and wood chips carried on conveyer belts. It has also been applied by KENT (1988) to fish meal and coffee and by CHOUIKHI (1988) to potato powder. This worker used a simple RF probe at 100 MHz. Both observed that the technique was more effective at lower moisture contents. An improvement on the Meyer/Schilz density independent function has been developed by POWELL et al. (1987). A homodyne microwave circuit was assembled to determine attenuation and phase shift so that the modified function could be evaluated. The method could be applied to flowing grain where the density variation is considerable.

Near Infrared Reflectance (NIR):-

This technique, whilst having the advantage of being non-contact, does only indicate moisture within the surface layer and hence is only applicable to measurement of grain moisture under

equilibrium conditions. Laboratory analysers are not well suited to measurement of grain moisture on the farm because they are expensive and fragile instruments. However, recent developments, in which the near infrared source is a light emitting diode, indicate that portable or solid state instruments can be developed that would be suitable for measuring grain moisture in the field. The essence of the method (BOWMAN et al., 1985) is that the sample is irradiated by an electrically pulsed light emitting diode with the reflected radiation being detected by a wide band photo diode. A reference LED is also necessary to allow automatic correction for variations in surface texture (and hence reflectivity) of the sample.

A battery powered portable instrument based on this technique and incorporating a single chip microprocessor to control the LEDs and to store calibration equations has been designed for measuring grass moisture content in the field (STAFFORD et al, 1988) over the range 15% - 95% wet basis. This instrument has been evaluated on small seed and could be calibrated for static samples of grain. Accuracy may be insufficient on whole grain but would be increased by grinding the sample.

An automatic NIR system, using off-line samples, has been described by MARIS (1988) for monitoring moisture content of flour in a mill. Moisture determined by the automatic system was within 0.1% compared with measurements in a laboratory NIR analyser or by oven drying.

Psychrometry:-

Where the humidity of air in a mass of grain is in equilibrium with the grain moisture content, as in a grain store, moisture may be inferred from measurement of humidity. A miniature temperature controlled psychrometer has recently been developed by MCBURNEY (1987) for use in measuring plant water potential by being strapped to the stem of the plant. Further development of the device into an integrated thin film form is being undertaken at AFRC Institute of Engineering Research. As the device is very

small and essentially robust, an array of such devices could be installed in a distributed moisture measurement system in a grain store. In integrated form, the cost would be acceptably low.

Acoustic methods:-

The elastic properties of grain vary with moisture content and hence the characteristic noise generated by grain falling onto grain or onto a rigid surface varies with moisture content. MEXAS and BRUSEWITZ (1986) used this principle to design a moisture meter based on measuring the sound level generated by flowing grain. In principle, the grain was caused to flow through a funnel in the conveying system and a microphone was situated adjacent to the funnel with its output being indicated on a sound level meter. The sound level was shown to be well correlated with grain moisture content in the range 10% to 18% but no indication of accuracy was reported.

Nuclear Magnetic Resonance (NMR):-

Pulsed NMR can be used to determine hydrogen nuclei in a material and thus the proportion of water and its forms. The technique requires a high quality magnet system and so is expensive. BRUSEWITZ and STONE (1987) have evaluated a commercial NMR instrument on wheat samples. They observed a very high linear correlation between the free induction decay ratio and grain moisture content over a range of 8-15%. Moreover, the relationship was not significantly affected by a 15% variation in bulk density.

C. Techniques used in other Industries

Measurement of moisture content is the main sensing requirement identified in a number of other industries. The techniques already described in this report have been evaluated in the process industries where there is a particular need for on-line measurement. Currently, near infrared and microwave absorption methods are commercially available but are not entirely satisfactory. Two techniques have been studied in recent years

for measuring soil moisture content. One is nuclear magnetic resonance (NMR) where some success in surveying soil moisture content across a field has been obtained by PAETZOLD (1987) using tractor mounted NMR equipment. The other technique is time domain reflectometry (TDR) where twin probes are inserted into the soil and a high frequency electromagnetic pulse is reflected at the soil-probe interface. The propagation velocity along the probes depends on the dielectric constant of the surrounding medium and hence moisture content can be determined by measuring the pulse delay. Application of techniques such as TDR to grain moisture content awaits experimental evaluation. However, both TDR and NMR techniques are expensive.

D. Prospects for Commercial Development

Of the studies described in section B above, the capacitive, microwave and psychrometric techniques would appear the most likely of commercial exploitation. For the dynamic situation of flowing grain, the two-frequency capacitative technique is attractive because of its low cost, whilst the microwave technique, though expensive, has the attraction of being non contact.

Chapter 7 Conclusions and recommendations

i) Conclusions:-

A. Moisture in grain, its measurement and significance are poorly understood.

The experiences of both authors of this review tend to confirm that many of the moisture-related practical problems which occur during the storage or trading of grain stem from fundamental misunderstanding of moisture, its measurement and particularly its significance. Perforce, much of the information on this subject is anecdotal, but one readily understood example is the rejection of loads that took place when grain was first offered into intervention in the U.K. As stated earlier, this occurred because the offerers of grain had no experience of a system that did not allow a margin of error at the maximum limit and, more importantly, because there was a widespread failure to appreciate that the use of different methods of measuring moisture could affect the results obtained.

Similarly, there seems to be little realisation of the importance of intergranular relative humidities and how they are controlled. Many storage problems, particularly those attributed to mites, occur because the storer does not realise that at the particular temperature/moisture content combination chosen for storage, the development of pests is almost inevitable. In terms of practical storage, cooling can equal drying, yet this concept seems to be very poorly understood by those storing grain. The situation is not helped by the lack of understanding of much of the terminology associated with moisture and its measurement.

Many of the errors that are blamed on moisture meters or oven methods are, in fact, not associated with the methods. Poor sampling, operator error and incorrect use of the equipment, are perhaps the causes of the most frequent and largest errors. Unfortunately, such sources of error are frequently overlooked.

B. Standardisation of measurement.

The use of more than one standard method of measuring moisture adds considerably to the problem of measurement. The case for adopting a single standard seems overwhelming and, in practice is occurring. BS 4317, in its increasing acceptance in the U.K., and more widely as ISO 712, is not free of problems such as operator error. However, the degree of penetration of this method through the industry so far is a compelling reason for its adoption as a single standard. The universal use of BS 4317 should be encouraged, as should the calibration of all moisture meters to this standard.

Oven based methods are supposed to provide the general standard for determination of moisture. However, there is a substantial body of data to show that there is variation between and within methods. More research and development is needed to investigate and quantify problems, and to develop solutions. In other countries, regular ring testing of such standard methods is carried out to address this problem.

Nuclear magnetic resonance (NMR) offers, in principal, the possibility of an accurate and rapid method of determining the moisture content of cereal grains. It is conceivable that a standard method, based on this technique, could be developed to replace BS4317 as the industry standard. Such a method would have clear advantages in speed of execution and would be potentially less vulnerable to operator error.

C. Need for improved rapid methods of measurement.

The accuracy and repeatability of currently available rapid methods have not changed significantly for many years. There would appear to be scope for more research and development to overcome the problems outlined in Chapter 3. In particular, the effects of variety, seasonal changes or stage of maturity have

not been sufficiently investigated. A national or international performance standard for rapid test methods would also be of great value to purchasers of equipment and would also benefit the manufacturers.

D. On-line and in-situ moisture measurement.

The information available to drier or store operators could be enhanced by the use of instruments providing a continuous flow of information during drying or storage. However, the current lack of suitable equipment restricts this option and also limits the use that can be made of recent advances in mathematical modelling of the drying process and of the potential for development of automated drier control. Continuous monitoring of temperature and moisture during storage would help pest management processes and reduce labour costs.

ii) Recommendations:-

A. WE RECOMMEND - that mechanisms for the dissemination information between scientists and technicians, farmers and storekeepers are improved. Steps should also be taken to provide better guidelines on the methodology of moisture measurement. Organisations such as NFU, GAFTA and UKASTA should be asked to consider how they can ensure that their members are fully versed in the subject. In addition, the production of a simple but comprehensive guide to moisture determination should be produced and made available to the widest possible audience.

B. WE RECOMMEND - that BS 4317 be adopted as a basis for all determinations of moisture during commercial transactions. All moisture meters sold in the U.K. should be calibrated to this standard and should be clearly marked to show that this is the case.

C. WE RECOMMEND - research should be undertaken to define standard techniques and equipment used to mill grain before oven testing for moisture. The setting up of a system of

ring testing in the U.K. to check the accuracy and repeatability of oven-based methods of moisture measurement should be considered, as should further research on improvements to oven methods. This latter would include work on whole-grain determinations and the effect of oven types. Ways of funding the above programme needs careful consideration.

In addition, a programme of research should be commissioned to develop a standard NMR moisture meter that would have potential to replace BS 4317 as the accepted commercial method of determining moisture in grain.

D. WE RECOMMEND - that a standard test protocol be drawn up for rapid moisture test methods and a programme of testing introduced. The possibility of adopting the current international standard procedure for testing moisture meters (ISO 7700/1) should also be considered as part of this research.

Consideration should also be given to setting up a national centre for testing, and perhaps approval of, moisture measuring devices and techniques. An indication of support for this suggestion has been received from two U.K. manufacturers of moisture meters.

E. WE RECOMMEND - that manufacturers and research organisations should co-operate in the development of suitable sensors, data capture systems and automated assessment techniques. Consideration should be given to setting up jointly funded projects between, for example, a manufacturer, a research institute and the grain industry.

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