TECHNICAL NOTE No. 101

METEOROLOGY AND GRAIN STORAGE

by

C.V. SMITH and M.C. GOUGH

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FOREWORD

On the recommendation of the Commission for Agricultural Meteorology (CAgM), Mr. C.V. Smith (United Kingdom) was requested to expand and rewrite the report of the Working Group on the Meteorological Aspects of the Storage of Cereals and Other Seed Crops. Mr. Smith’s report was published as WMO Technical Note No. 101 in 1969.

The eighth session of the Commission considered that this Technical Note needed up-dating and revision and appointed Mr. M.C. Gough as rapporteur on the topic. The up-dated and revised report is now published as Technical Note No. 101 (revised).

I take this opportunity to thank Mr. Gough for the time and energy spent by him in bringing out this revised publication.

(G.O.P. Obasi)
ACKNOWLEDGEMENTS

This note is a revision of Meteorological and Grain Storage by Mr C. V. Smith, World Meteorological Organization Technical Note No. 101. Mr Smith was especially helpful during the preparation. Thanks are extended to staff at the United Kingdom Overseas Development Natural Resources Institute who provided selected inputs; Messrs R. A. Boxall, J. A. Hallam and E. T. O'Dowd and Dr R. A. Hodges were particularly supportive. Dr B. A. Callander at the United Kingdom Meteorological Office is gratefully acknowledged for his assistance.
The overall minimum losses of durable crops by damage or deterioration during storage have been estimated to be 10% with wide variations. Such losses are of serious economic consequence, and may nullify the gains that might be expected to follow from the introduction of new varieties or improved farming techniques.

Much of this damage is caused by mycological, entomological and other agents, all of which are influenced by environmental factors. A technical note (WMO T.N. No. 101) examined Meteorology and Grain Storage. By 1983 it had become outdated and the Commission for Agricultural Meteorology, at its Eighth Session, commissioned a review of progress since that technical note had been written (Resolution 7, CAgM-VIII). The review presented here is in the form of an updated version of Technical Note No.101.

Chapter 1 examines the biological characteristics of the grain and of stored products pests. For safe storage, biological activity should be at a minimum, and this section sets out the combinations of temperature and moisture content of the grain (and the intergranular air) which inhibit the growth of stored products insects, mites and moulds, and which preserve the viability of the grain.

Chapter 2 looks at the important physical characteristics of grain. Brief reference to the moisture absorption characteristics of a colloidal material such as grain is followed by a description of the effect of temperature changes on the equilibrium water vapour pressure exerted by grain. Reference is made to the transfer of moisture by air convection currents and by thermally generated diffusion within a grain bulk and to the effect of humid air surrounding a stack of bags of grain. The rate of heat transfer into stored grain is considered, together with the intergranular air exchange induced by barometric changes.

Chapter 3 is concerned with the preparation of grain for safe storage. Factors which influence the temperature, moisture content and storage potential at harvest time are mentioned. Natural and artificial methods of drying are described.

Chapter 4 deals with the procedures used to maintain a grain bulk in good condition. The impracticability of depending on natural ventilation to do this in some methods of storage leads to the use of forced ventilation for maintenance of satisfactory grain temperatures and moisture contents. This is followed by reference to the methods of grain chilling and air-tight storage.

Chapter 5 describes instruments and procedures to monitor temperatures and moisture contents within grain bulks.

Chapter 6 sets out some ways in which the agricultural meteorologist might advise in the construction and location of grain stores, in raising the storage potential of the field crop, and in the safe-keeping of stored crops.

The report includes a selected bibliography of the literature on the subject of relationships between climate and grain storage.
RESUME

On a estimé à 10% (chiffre qui peut varier largement) les pertes minimum globales de cultures non périssables dues à des dégâts ou une détérioration survenant en cours de stockage. Ces pertes ont des répercussions économiques graves et peuvent même complètement annihiler les avantages qui découleraient de l’introduction de nouvelles variétés ou de la mise en application de techniques agricoles perfectionnées.

Ces dégâts ou détériorations sont causés en grande partie par des agents entomologiques, mycologiques ou autres qui sont influencés par les conditions du milieu. Une note technique (WMO T.N. No 101) a donc été consacrée à la question de la météorologie et de l’emmagasinage des graines. En 1983, cette note technique était dépassée, la Commission de la météorologie agricole a demandé à sa huitième session que les progrès enregistrés depuis la rédaction de la note technique soient étudiés et enregistrés (Résolution 7, CMAg-VIII). Cette étude fait l’objet du présent ouvrage, qui est une version mise à jour de la Note Technique No.101.

Le premier chapitre étudie les caractères biologiques des céréales et des parasites des silos. Pour que le stockage soit sans risque, l’activité biologique devrait être minimale et ce chapitre définit donc les combinaisons de températures et de degrés hygrométriques de céréales (et de l’air ambiant) qui empêchent la croissance des parasites des silos, des acariens et des moisissures, et qui préservent la viabilité des céréales.

Le chapitre 2 est consacré aux caractéristiques physiques des céréales. Un bref examen des caractéristiques d’absorption de l’humidité d’une matière colloïdale telle que les céréales est suivie d’une étude des effets des variations de température sur l’équilibre entre la tension de vapeur d’eau du grain et celle d’une surface d’eau libre. Sont également mentionnés le transfert de l’humidité par les courants de convection et par une diffusion d’origine thermique au sein de céréales stockées en vrac et les effets de l’air humide entourant une pile de sacs de grains. La question de la vitesse de transfert de la chaleur dans les céréales emmagasinées est ensuite abordée, ainsi que celle de l’échange d’air ambiant résultant des variations de la pression.

Le chapitre 3 est consacré à la préparation des céréales en vue de leur stockage optimal et indique les facteurs qui ont un effet sur la température, la teneur en humidité et les possibilités de stockage au moment de la récolte, ainsi que les méthodes naturelles et artificielles de dessication.

Le chapitre 4 traite des méthodes utilisées pour maintenir en bon état le grain stocké en vrac. Comme il est impossible, avec certaines méthodes de stockage, de compter sur la ventilation naturelle, on est amené à utiliser la ventilation forcée pour maintenir la température et la teneur en humidité des céréales à un niveau satisfaisant. Suit une indication des méthodes utilisées pour réfrigérer les céréales et les stocker dans un milieu étanche à l’air.

Le chapitre 5 décrit les instruments et les méthodes utilisées pour contrôler la température et la teneur en humidité des céréales stockées en vrac.

Le chapitre 6 indique quelques des manières dont le spécialiste de météorologie agricole pourrait jouer un rôle de conseiller dans la construction et le choix de l’emplacement des silos à grains, l’accroissement des possibilités d’entreposage des produits agricoles et la bonne conservation des stocks de céréales.

Le rapport se termine par une liste d’ouvrages qui traitent du lien entre le climat et le stockage des céréales.
РЕЗЮМЕ

Минимум потерь продовольственного зерна (злаковых) в результате повреждения или порчи при хранении оценивается в 10% при очень большом разбросе. Эти потери имеют очень серьезные экономические последствия и могут перевешивать выгоды, получаемые в результате выведения улучшенных сортов и более совершенных агротехнических методов.

Значительная часть этих потерь вызывается микологическими, энтомологическими и другими агентами, на которые оказывают воздействие факторы окружающей среды. Вопросы метеорологии и хранения зерна исследовались в технической записке (ВМО, ТЗ № 101). К 1983 г. записка потеряет свою актуальность, и Комиссия по авиационной метеорологии на своей восьмой сессии решила подготовить обзор достижений в этой области в виде технической записки (рекомендация 7, КСхМ—VIII). Здесь, в форме обновленного варианта Технической записи № 101, представляется этот обзор.

В первой главе рассматриваются биологические характеристики продовольственных зерновых культур и связанных с ними потенциальных вредителей. Для устранения потерь при хранении биологическая активность должна быть сведена к минимуму, и в данном разделе устанавливаются соотношения температуры и влагосодержания зерна (а также внутреннего газообмена), способствующие инактивации или размножению насекомых, клещей и плесени и сохранению жизнеспособности зерна.

Вторая глава посвящена важным физическим характеристикам зерна. После краткой характеристики процессов абсорбции влаги коллоидным материалом, каким является зерно, обсуждаются влияние температурных изменений на равновесное давление водяного пара, выделяемого зерном. Обсуждаются также проблемы, связанные с переносом влаги конвекционными потоками внутри массы зерна, находящегося навалом, а также влияние влаги, воздействующей на наружную поверхность массы зерна. Рассматриваются вопросы о скорости прохождения тепла внутри массы находящегося зерна, а также о воздухообмене, вызываемом изменениями давления.

Глava 3 посвящена подготовке продовольственного зерна для хранения. Обсуждаются факторы, влияющие на температуру, влагосодержание и возможности хранения при уборке урожая. Дается описание естественных и искусственных методов сушки зерна.

Четвертая глава посвящена используемым методам сохранения массы зерна в хорошем состоянии. Надежность методов естественной вентиляции в больших случаях приводит к использованию принудительной вентиляции с целью поддержания необходимой температуры и влагосодержания. Описываются также методы охлаждения зерна и хранения зерна в воздушонепроницаемых помещениях.

В главе 5 дается характеристика приборов и методов мониторинга температуры и влагосодержания в массе зерна.

Глava шестая посвящена проблеме участия специалистов по сельскохозяйственной метеорологии в строительстве и размещении зернохранилищ, в улучшении возможностей хранения сельскохозяйственных культур и предотвращении потерь продовольственного зерна при хранении.

В докладе дается также выборочный список литературы по вопросам продовольственного зерна.
Las pérdidas mínimas globales de cosechas duraderas por daños o deterioración causadas por el almacenamiento se calculan del orden del 10 por ciento. Tales pérdidas tienen graves consecuencias económicas y anulan por completo las ganancias que cabría esperar como consecuencia de la introducción de nuevas variedades o de técnicas agrícolas perfeccionadas.

Muchos de estos daños los producen los agentes micológicos, entomológicos o de otro tipo, todos ellos influidos por los factores ambientales. En una nota técnica (Nota Técnica N°. 101 de la OMM) se examinó la cuestión de la Meteorología y el almacenamiento de granos. Esta nota estaba anticuada en 1983 y la Comisión de Meteorología Agrícola, en su octava reunión, encargó un estudio sobre los progresos que se habían realizados desde que se redactara dicha Nota Técnica (Resolución 7 de la septima reunión de la CMAd). El examen que contiene el presente documento técnico presenta una versión actualizada de la Nota Técnica N°.101.

En el Capítulo 1 se examinan las características biológicas de los cereales y de pestes de productos almacenados. Para que los cereales se puedan almacenar con seguridad, la actividad biológica debe ser mínima, y en esta sección se indican las combinaciones de temperatura y de humedad de los cereales (y del aire intergranular) que impiden la proliferación de los insectos, ácaros y mochos, y conservan la viabilidad del grano.

En el Capítulo 2 se examinan las importantes características físicas de los cereales. Se hace una breve referencia a las características de absorción de la humedad de una sustancia coloidal como es el grano, seguida de una discusión del efecto que ejercen los cambios de temperatura sobre la presión de equilibrio del vapor ejercida por el grano. Se hace referencia a la transmisión de humedad por las corrientes de convección y por la difusión generada térmicamente en los cereales almacenados a granel y a los afectos del aire humedo que rodea a sacos acumulados de cereal. Se plantea la cuestión de la velocidad de transmisión del calor en el grano almacenado, junto con el intercambio de aire intergranular provocado por cambios barométricos.

El Capítulo 3 trata de la preparación que necesitan los cereales alimenticios para poderlos almacenar con seguridad. Se mencionan los factores que influyen en la temperatura, humedad y potencial de almacenamiento en la época de la recolección. Se describen métodos naturales y artificiales de secado.

El Capítulo 4 trata de los procedimientos utilizados para mantener en buenas condiciones los cereales almacenados a granel. La impracticabilidad de depender de la ventilación natural para conseguirlo en algunos métodos de almacenamiento conduce al uso de una ventilación forzada para poder mantener temperaturas y humedades satisfactorias. Se hace después referencia a los métodos de refrigeración de los cereales y al almacenamiento sin contacto con el aire.

El Capítulo 5 se refiere a los instrumentos y procedimientos para controlar la temperatura y la humedad de los cereales almacenados a granel.

El Capítulo 6 trata de los procedimientos a través de los cuales el meteorólogo agrícola puede asesorar en la construcción y emplazamiento de los almacenes de cereales, en el aumento del potencial de almacenamiento de los cultivos extensivos y en el mantenimiento de seguridad de las cosechas almacenadas.

En el informe figura una selección de la bibliografía actual sobre la relación entre el clima y el almacenamiento de cereales.
A new variety of cereal, produced after many years of selection and field trial may result in a yield increase of perhaps 10% over earlier varieties. The losses of the food grains harvested in any one year have been variously estimated and it is widely acknowledged that losses in storage are serious. Conservative expert opinion resists generalisations of loss estimates because they cannot be substantiated by statistically sound data, but for planning purposes experts often cite a minimum overall loss of 10% for durable crops (National Academy of Sciences 1978). However, much depends upon local circumstances. Whilst it has been shown that storage losses in the truly traditional farming system are contained at around the 5% level the changes consequent upon the introduction of new varieties of cereals disturb the traditional capability to conserve grain and increase the risk of loss. The new varieties not only increase production they also place a strain on available storage capacity and are themselves more susceptible to deterioration in storage. (Tyler and Boxall 1984). There are then opportunities for improvement in the short term, which would complement the longer term approach of the plant breeder and agriculturalist.

To the agricultural meteorologist, the construction of a store to conserve a grain bulk is an exercise in weather proofing; that is, in local climate modification or in environmental control. The grain interacts with its environment, exchanging heat and moisture. The level of biological activity, both of the grain itself and of its associated (and potentially damaging) organisms, frequently shows a positive response to the environment found within grain. Successful conservation requires that this biological activity be minimised. In general, the ideal ranges of the physical characteristics of grain and its environment can be specified. Success in conservation depends upon achieving and maintaining the food bulk within these ranges.

However, damage during storage is not likely to be simply a linear function of the departure from the known optimum conditions. When biological thresholds are crossed, the resultant biological response may be not only self-maintaining but self-generating. Even if the multiplication of pathogenic fungi, mites and insects, are excluded, the respiration rate of the seed grains will increase by a factor of about two for a 10°C rise in temperature. An increase in respiration rate will lead, through the breakdown of organic material to an increase in moisture content of the grain and to an increase in metabolism from this cause. Even small foci of damage can lead to a rapid deterioration of the food bulk as a whole. Partial control is not enough. The aim must be to prevent any part of the bulk passing critical levels of temperature and moisture content.

Since the primary physical factors in grain storage are the temperature and moisture content of the grain and the relative humidity of the intergranular air the agricultural meteorologist is led on to consider instrumentation that will measure and monitor these variables. In order that
the physical characteristics of the grain can be manipulated, it is necessary to understand the physics of the interaction between the stored bulk grain and its intergranular atmosphere and between the bulk and its immediate environment in the store. The weather can influence the microclimate within the store. This factor is important at the design stage of store building. Insulation and ventilation requirements are relevant to prime building costs. If, for example, control and conditioning of the food bulk is likely to be achieved by forced ventilation, then some knowledge of the probable external environment may enable estimated running costs to be made or the relative advantage of alternative sites. Weather records must be used to provide long-term planning data.

Instrumentation, knowledge of heat and moisture transfer processes, and applied climatology, all assist the meteorologist in his approach to this problem. However, even consideration of these more immediate factors may not be entirely adequate. The preceding growing season will have its effect on the extent and severity of attack by pests and disease on the growing crop and on the numbers of pathogenic organisms and damaged grains carried into store. The weather around harvest time may determine the stage of maturity and the moisture content of the crop and the extent of the physical damage incurred during harvest. All these factors are relevant to keeping quality. In the same way, the success of post-harvest field treatments, in preparation for long-term storage, is likely to be dependent on the weather. Repeated wetting and drying may split the outer layers, and a broken grain is open to invasion by moulds and insects.

It may be that the meteorologists can do no more than give forecasts or warnings of the probable extent of field damage by pest or disease in a particular season. If the meteorologist is to be specific about matters of which the farmer is probably already aware in general, then field observations become necessary to establish the initial correlation between the weather of the season and the state of the grain leaving the field.
CHAPTER 1

BIOLOGICAL CHARACTERISTICS OF FOOD GRAINS
AND ASSOCIATED ORGANISMS

1.1 VIABILITY OF THE GRAIN

The most sensitive property of a seed is perhaps its ability to germinate. For safe storage, when the object is the maintenance of viability, it is essential to use seeds that are sound, well matured, of high initial viability, and of low moisture content (mc).

Germination suffers as a result of attacks by insects, mites, moulds and bacteria, from storage at high temperatures or at high levels of mc (or both) or merely as a result of prolonged storage.

The two principal physical factors affecting the viability of seeds in storage are seed mc and seed temperature. Under ideal storage conditions, both are kept low, but in practice it may be sufficient to control one of these variables. Of the two, a low seed mc is the more important, for loss of viability is accelerated more by a high mc than a high storage temperature.

Acceptable combinations of seed temperature and mc for safe storage are shown in Figure 1.

In dry regions, the mc of naturally dried seeds may be sufficiently low for safe storage, but in more humid climates it will probably be necessary to resort to artificial drying prior to storage and/or possibly to some conditioning of the food bulk during storage (O'Dowd and Dobie, 1983).

Cereal grains can achieve great permanence in store, since their level of metabolic activity in the dormant state is comparatively low, but sufficient to offer resistance to decomposition by micro-organisms. This resistance to decomposition is mechanical rather than dynamic. It is dependent upon presenting an unbroken outer surface to the invading organisms rather than the production of reactions toxic to their presence or to the development of scar tissue. Dormancy is controlled by seed mc, and to store grain that is insufficiently dry will soon bring this period of relative inactivity to an end. In respiration, energy is released through the oxidation of organic material, mostly carbohydrates and fats. Heat, water and carbon dioxide are evolved. Figure 2 shows the effect of increasing seed mc (at a given temperature) on the respiration of seeds: respiration is measured by the output of carbon dioxide. The Van't Hoff rule for the rate at which certain chemical reactions proceed with change of temperature also applies to certain biological processes. The temperature coefficient of the respiration rate for seeds suggests a doubling of the respiration rate for a 10°C rise in temperature. Increasing respiration rates and a mobilization of food reserves can lead to sprouting. Sprouting within a food bulk is followed by rotting.
Seeds, being hygroscopic, exchange water vapour with their environment, and at equilibrium there is a fixed relationship between seed mc and the relative humidity (rh). Figure 3 shows for several intergranular crops the form of this relationship, which proves to be largely independent of temperature. The different types of grain vary in their equilibrium values, and Figure 3 must be considered more as a guide than as indicating definitive values. It is known, for example, that different varieties of one type of grain (e.g. yellow and white maize, hard and soft wheats) may differ in their equilibrium mcs by perhaps 1%-2%. In addition, in a cycle of wetting and drying, the equilibrium curve may exhibit hysteresis and than the equilibrium mc depends upon whether the equilibrium value is approached from higher or lower mcs.

For many important food grains a mc of the order 13%-15% (wet-weight basis) corresponds to an ambient equilibrium rh of about 70%.

1.2 FUNGI

For practical purposes a rh of 70% is sometimes considered critical in that fungi, often a primary cause of loss of viability and quality require at least this level of ambient moisture to support multiplication. Figure 4 shows the temperature and rh of the intergranular air at which various species of fungi may cause damage. However, some fungi are known to grow at rh as low as 62% (corresponding to a grain mc of perhaps 11%-13%, wet-weight basis).

The rate of reproduction of fungi increases (within limits) with temperature. It may not be practicable to prevent mould growth entirely by temperature control, since a number of moulds can still grow at temperatures below 0°C. However, at such low temperature, the rate of multiplication of the fungi may be such that damage remains negligible. Storage even at 5°C may result in visible mould growth in about 2 months at mcs in excess of 22% (wet-weight basis). Maximum mould growth is achieved at about 35°C-40°C. Figure 5 shows the interaction of temperature and ambient rh on the rate of development of two species of the mould Aspergillus. The form of the curves may be considered typical. The plant and growing cereal seed are normally invaded by various field fungi (Christensen, 1957), and some superficial micro-organisms will always be present on grains brought into store. More importantly, sub-epidermal fungal mycelium can be shown to be abundant in many samples of grain. Their numbers and predominant species are presumably a reflection of the weather during the growing season, and of the harvest and post-harvest weather. For example, Machacek et al. (1951) show Nigrospora to be normally present on cereals in western Canada. These same authors report on Nigrospora sphaerica: "Although occurring in all the seed inspection districts, it was particularly prevalent in Manitoba during 1940 and 1941, when excessively wet weather delayed threshing of swathed grain." (This statement on time in the swath is revealing in another context. Smallman (1942) reports a severe outbreak of the mite Aculus siro (which feeds both on the grain kernel and on fungi) in stores in Manitoba and other parts of Canada in 1940-1941).
The two most common and important field fungi are, on healthy grain, *Alternaria* and *Helminthosporium*. The storage fungi *Penicillium* and *Aspergillus* are extremely common in heating grain.

The presence of fungal mycelium must always be assumed, but damage to the grain is not inevitable. Conditions must favour the multiplication, and the grain must be open to invasion.

Damage to the grain at harvest arises in two ways. Dry grain, being brittle, breaks easily and provides a readily available substrate for the fungal growth if conditions are right. Damp grains suffer compression, during which protective tissues are damaged.

Damage to the grain in store by fungal attack will be hindered or inhibited by control of the temperature and more importantly the use of MC of the grain and by harvesting and handling procedures which maintain the protective external tissues intact. The removal of weed seeds and broken grains (dockage) recommends itself. There is no evidence that cereals secrete chemicals which inhibit pathogenic fungi, but the deliberate addition of organic acids (e.g. propionic acid) to a bulk is one method that has been used to facilitate the safe-keeping of moist grain.

The thermal characteristics of bulk grain are such that any heat generated within the bulk is dissipated only very slowly. Quantitative calculations suggest that the spontaneous heating of bulk grain (wheat) due to the metabolism of the grain alone is most unlikely if the grain MC is less than about 14% (wet-weight basis). Spontaneous heating of the bulk occurs with damper grain (i.e. with a MC in excess of 14%-15%) and in most cases with a MC in excess of 17%-18%. This is partly due to the metabolism of the grain, but arises chiefly from the respiration of fungi infecting the grain. The cumulative effects and the spread of these self-induced temperature (and concomitant moisture) changes are such that grain temperatures approaching (but seldom in excess of) 62°C may be reached.

1.3 INSECTS

When grain drier than 14% MC (wet weight basis) undergoes a spontaneous increase in temperature, the heat source is not the metabolism of the grain itself, but rather the metabolism of insects infesting the bulk. Dry grain heating is characterized by temperatures which may approach 38°C to 42°C. This temperature level is critical in that the insects that attack stored grain are killed by exposure to higher temperatures. One effect of temperature differences within a cereal bulk will be the establishment of convective air currents (Gough, et al., 1987). Because of the coupling between head space and bulk moisture exchange processes, water vapour movement down temperature gradients by diffusion takes place. If this translocation of moisture leads to locally damp grain, then an initial outbreak of dry grain (insect) heating may be superseded by damp grain (fungal) heating with its characteristically higher maximum temperatures. The processes are shown schematically in Figure 6.
In most temperate climates, the insects which attack grain in the field are not those which give trouble during storage. If, in these climates, "combining" is considered as the usual harvesting method, then grain fresh from the field could be considered free from insect infestation. But if for any reason there is any considerable delay in threshing, either through swath drying or through stacking the sheaves in some way, then insects may be brought into store with the grain.

As a group, most of the insects which damage stored grain are of tropical or sub-tropical origin. Part of their life cycle may be spent within the grain where they cannot be detected by simple inspection at this stage. These insects do not hibernate, so that their ability to persist and breed outside of the tropics and sub-tropics is dependent upon their finding or creating the right kind of microclimate, either within a food bulk or within the fabric of a food store. Table 1.1 lists some of the major insect pests of food grains in the tropics and sub-tropics.

The list (Table 1.1) is not intended to be exhaustive, either for for insects or the food grains they attack. It certainly does not preclude these insects being found in food bulks outside of the tropics. Hurst (1964) has discussed the airborne spread of insects over thousands of miles, but the normal source of infestation of grain in temperate latitudes must almost inevitably be contamination prior to transportation from a warmer climate or the survival within a store of insects among the residues of a previously infested bulk.

Of the insects which damage grain in store, a few begin their attack in the field several weeks before harvest. Among these the weevils Sitophilus zeamais and Sitophilus oryzae are important. Other insects start their attack after cutting and during the field-drying prior to long-term storage. As the moisture content of the grain is reduced by this drying, so the insect species which preponderate may change. The moth Mussidia spp. on cob maize at harvest dies out during storage; Bruchidius atrolineatus, which infests cowpeas in the pod in the field, also dies out in store but is replaced by Callosobruchus maculatus (Caswell, 1961).

Each of the insect species that attack stored grain has a characteristic range of environmental conditions that permits its survival and development. Some species will be more tolerant of higher humidities than others, principally because they feed not on the sound grains directly, but either on moulds or on the grains after they have been decomposed by moulds.

The environment within the seed bulk may be considered as specified by the relative humidity of the intergranular air (i.e., the equilibrium moisture content of the grain), by the grain temperature and by the amount of dockage (the numbers of damaged grains).

The relevance of moisture content is illustrated (Table 1.2) by part of a table due to Cotton, et al., (1953).
## Table 1.1

Major Insect Pests of Food Grains

<table>
<thead>
<tr>
<th>Insect species</th>
<th>Scientific name</th>
<th>Produce attacked</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weevils</td>
<td><em>Sitophilus</em> spp.</td>
<td>Maize, sorghum, wheat, rice, paddy</td>
</tr>
<tr>
<td>Lesser grain borer</td>
<td><em>Rhyzopertha dominica</em> (F.)</td>
<td>Paddy, rice, wheat, pulses, cassava</td>
</tr>
<tr>
<td>Khapra beetle</td>
<td><em>Trogoderma granarium</em> (Everts)</td>
<td>Maize, wheat, sorghum, groundnuts, pulses</td>
</tr>
<tr>
<td>Saw-toothed grain beetles</td>
<td><em>Oryzaephilus</em> spp.</td>
<td>Maize, wheat, rice, groundnuts</td>
</tr>
<tr>
<td>Flour beetles</td>
<td><em>Tribolium</em> spp.</td>
<td>Maize, wheat, flour, groundnuts</td>
</tr>
<tr>
<td>Pulse beetles</td>
<td><em>Callosobruchus maculatus</em> (F.)</td>
<td>Cowpeas, lentils, grams</td>
</tr>
<tr>
<td></td>
<td><em>Callosobruchus analis</em></td>
<td>Cowpeas, lentils, grams</td>
</tr>
<tr>
<td></td>
<td><em>Acantoscelides obtectus</em> (say)</td>
<td>Beans (Phaseolus)</td>
</tr>
<tr>
<td></td>
<td><em>Zabrotes subfasciatus</em> Boheman</td>
<td>Cowpea, beans (Phaseolus)</td>
</tr>
<tr>
<td></td>
<td><em>Careydon gonagra</em> (F.)</td>
<td>Groundnuts</td>
</tr>
<tr>
<td>Flat grain beetles</td>
<td><em>Cryptolestes</em> spp.</td>
<td>Maize, rice, groundnuts, cocoa, flour</td>
</tr>
<tr>
<td>Angoumois grain moth</td>
<td><em>Sitotroga cerealella</em> (Oliv.)</td>
<td>Maize, wheat, paddy, sorghum</td>
</tr>
<tr>
<td>Tropical warehouse moth</td>
<td><em>Ephestia cautella</em> (Walker)</td>
<td>Groundnuts, rice, maize wheat, cocoa, sorghum</td>
</tr>
<tr>
<td>Indian meal moth</td>
<td><em>Plodia interpunctella</em> (Hubn.)</td>
<td>Maize, rice, paddy, groundnuts</td>
</tr>
<tr>
<td>Rice moth</td>
<td><em>Corcyra cephalonica</em> (Staint.)</td>
<td>Maize, wheat, paddy, rice</td>
</tr>
</tbody>
</table>
TABLE 1.2

EXAMPLE OF THE RELATION BETWEEN GRAIN MOISTURE CONTENT AND INSECT POPULATION

<table>
<thead>
<tr>
<th>% moisture content</th>
<th>8-8.9</th>
<th>9-9.9</th>
<th>10-10.9</th>
<th>11-11.9</th>
<th>12-12.9</th>
<th>13-13.9</th>
<th>14-14.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>wet-weight basis</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insects per 1000 g sample</td>
<td>2</td>
<td>9</td>
<td>8</td>
<td>12</td>
<td>11</td>
<td>18</td>
<td>37</td>
</tr>
</tbody>
</table>

TABLE 1.3

NUMBER OF DAYS EXPOSURE AT VARIOUS TEMPERATURES REQUIRED TO KILL ALL DEVELOPMENTAL STAGES OF VARIOUS STORAGE PESTS

<table>
<thead>
<tr>
<th>Insect</th>
<th>-18°C to -15°C</th>
<th>-15°C to -12°C</th>
<th>-12°C to -9°C</th>
<th>-9°C to -7°C</th>
<th>-7°C to -4°C</th>
<th>-4°C to -1°C</th>
<th>-1°C to +2°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rice weevil</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>6</td>
<td>8</td>
<td>16</td>
</tr>
<tr>
<td>Granary weevil</td>
<td>1</td>
<td>3</td>
<td>6</td>
<td>14</td>
<td>33</td>
<td>46</td>
<td>73</td>
</tr>
<tr>
<td>Saw-toothed grain beetle</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>7</td>
<td>23</td>
<td>26</td>
</tr>
<tr>
<td>Confused flour beetle</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td>12</td>
<td>17</td>
</tr>
<tr>
<td>Redflour beetle</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td>8</td>
<td>17</td>
</tr>
<tr>
<td>Indian meal moth</td>
<td>1</td>
<td>3</td>
<td>5</td>
<td>8</td>
<td>28</td>
<td>90</td>
<td>-</td>
</tr>
<tr>
<td>Mediterranean flour moth</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td>7</td>
<td>24</td>
<td>116</td>
<td>-</td>
</tr>
</tbody>
</table>
In general, the grain feeding insects will not survive or breed successfully in grain with a moisture content of perhaps 8% or less (corresponding to an equilibrium relative humidity of 40%). Figure 7 (after Davidson, 1940) makes this point.

An upper limit of 38°C to 42°C has already been mentioned for the temperatures that permit the survival of most of the relevant insects. Resistance to low temperatures is not well developed and Table 1.3 (after Cotton et al., 1953) indicates the effect of exposure to cold.

### Table 1.4

SHOWING THE MULTIPLICATION OF RHIZOPERTHA DOMINICA IN ONE GENERATION IN WHEAT OF VARIOUS MOISTURE CONTENTS AND TEMPERATURES

<table>
<thead>
<tr>
<th>% moisture content (wet-weight basis)</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>18.3°C</td>
</tr>
<tr>
<td>8% mc sound grain</td>
<td>-</td>
</tr>
<tr>
<td>damaged grain</td>
<td>-</td>
</tr>
<tr>
<td>9% mc sound grain</td>
<td>-</td>
</tr>
<tr>
<td>damaged grain</td>
<td>-</td>
</tr>
<tr>
<td>10% mc sound grain</td>
<td>-</td>
</tr>
<tr>
<td>damaged grain</td>
<td>-</td>
</tr>
<tr>
<td>11% mc sound grain</td>
<td>-</td>
</tr>
<tr>
<td>damaged grain</td>
<td>-</td>
</tr>
<tr>
<td>14% mc sound grain</td>
<td>0</td>
</tr>
<tr>
<td>damaged grain</td>
<td>0</td>
</tr>
</tbody>
</table>
CHAPTER 1

The importance of dockage is illustrated by reference to the lesser grain borer as shown in Table 1.4 (after Birch, 1945). A population of *Rhysopertha dominica* will die out in sound grains of 9% mc (at 26°C); but with damaged grains at the same mc and temperature, it may increase by some 50 times in one generation.

Figure 8 makes the same point concerning dockage and the survival of another species, the confused flour beetle (*Tribolium confusum*). Even the complete absence of food (and certainly the apparent total emptying of a silo) cannot be regarded as a safe way to eliminate the insect, unless the absence of food continues for a long time. Insects may be able to withstand starvation for long periods, especially at low temperatures (Table 1.5).

### TABLE 1.5

**SURVIVAL TIME OF TWO SPECIES OF INSECT WITHOUT FOOD UNDER VARIOUS CONDITIONS OF TEMPERATURE AND HUMIDITY (AFTER MATHELIN, 1938)**

<table>
<thead>
<tr>
<th>Insect</th>
<th>Survived days without food</th>
<th>Temperature</th>
<th>Relative humidity</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>S. oryzae</em></td>
<td>22</td>
<td>12°-14°C</td>
<td>45%</td>
</tr>
<tr>
<td></td>
<td>95</td>
<td>12°-14°C</td>
<td>70%-80%</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>25°C</td>
<td>38%-40%</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>25°C</td>
<td>75%-80%</td>
</tr>
<tr>
<td><em>S. granarius</em></td>
<td>45</td>
<td>12°-14°C</td>
<td>45%</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>12°-14°C</td>
<td>70%-80%</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>25°C</td>
<td>38%-40%</td>
</tr>
<tr>
<td></td>
<td>31</td>
<td>25°C</td>
<td>75%-80%</td>
</tr>
</tbody>
</table>

Most features of insect life e.g. egg laying, development, mortality, etc., are strongly influenced by environmental conditions. Figure 9 shows a typical series of curves (for one of the saw-toothed grain beetles) and demonstrates how the time for development from egg to adult varies with the ambient temperature and humidity. The development of the egg stage is also dependent upon the environment. Figure 10 shows, for example, how this varies with temperature for the species *Rhysopertha dominica* and *Sitophilus oryzae* at a given mc. In general, the grain-feeding insects will not breed successfully in an environment in which the temperature is less than 10°C. This statement is further exemplified by a second reference to the two species last mentioned. Figure 11 shows how the number of eggs produced varies with the ambient temperature and moisture content of the grain. The weakest link in the multiplication of the insects is always the larval stage. Figure 12 shows how mortality can vary with environmental factors. Similar interesting data on the effect of temperature and humidity on the development of *Callosobruchus maculatus* (F.), a serious pest of stored pulses, are given in Table 1.6.
TABLE 1.6
THE PERCENTAGE SUCCESSFUL DEVELOPMENT OF CALLOSOBURCHUS MACULATUS (F.)
UNDER DIFFERENT TEMPERATURE AND HUMIDITY CONDITIONS
(After Mookherjee and Chawla, 1964 - reproduced in part)

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Relative humidity (percentage)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>45</td>
</tr>
<tr>
<td>20</td>
<td>75</td>
</tr>
<tr>
<td>25</td>
<td>81</td>
</tr>
<tr>
<td>30</td>
<td>78</td>
</tr>
<tr>
<td>35</td>
<td>48</td>
</tr>
<tr>
<td>38</td>
<td>10</td>
</tr>
</tbody>
</table>

TABLE 1.7
PROGENY OF 50 PAIRS OF TWO WEEVIL SPECIES IN WHEAT AFTER 5 MONTHS

SITOPHILUS ORYZAE

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Grain moisture content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8%</td>
</tr>
<tr>
<td>16</td>
<td>0</td>
</tr>
<tr>
<td>21</td>
<td>0</td>
</tr>
<tr>
<td>27</td>
<td>0</td>
</tr>
<tr>
<td>32</td>
<td>0</td>
</tr>
</tbody>
</table>

SITOPHILUS GRANARIUS

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Grain moisture content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8%</td>
</tr>
<tr>
<td>16</td>
<td>0</td>
</tr>
<tr>
<td>21</td>
<td>0</td>
</tr>
<tr>
<td>27</td>
<td>0</td>
</tr>
<tr>
<td>32</td>
<td>0</td>
</tr>
</tbody>
</table>
As a measure of the rate of reproduction of grain-infesting insects, Cotton et al. (1953) have used as an indicator the number of progeny arising from 25 or 50 pairs of insects by the end of a 5-month period. Typical results are shown in Table 1.7.

This approach gives a direct measure of the probable insect numbers and of the cumulative effect of successive generations, but as the number of pairs taken and the elapsed time may be considered somewhat arbitrary, other measures suggested by Birch (1945) may at times be preferred. These are the multiplication in one generation and the rate of multiplication in 100 days (the biotic potential).

Birch adopted the following method:

Multiplication in one generation

\[ = \frac{1}{2} \times \text{total number of eggs per female} \times \text{percentage of eggs giving rise to adult insects} \]

Biotic potential

\[ = \text{Multiplication in 100 days (of the initial parent stock); or} \]

\[ = \text{Multiplication in one generation} \times 100/D \]

where \( D \) = Number of days for development from egg to adult.

Definitions such as these enable full use to be made of the kind of information developed in Figures 9 to 12.

Just as in field crops, examples can be found of the transfer of feeding preferences of pests from wild host plants to cultivated or introduced species, or of the development of new feeding habits following the introduction of an insect into a new environment. Stored-product insects, normally considered innocuous, may become a menace due to sudden changes in feeding habit. Ephesia cautella, for example, which normally attacks dried fruits and processed foods, has been increasingly reported as infesting groundnut, wheat, maize and hides. This has led to the work of Saroj et al. (1966), who report in detail on the temperatures and humidities that have been found acceptable or necessary for development and increase of this pest. The point is made that a grain store is always at risk.

1.4 MITES

Just as the presence of fungi can be demonstrated on almost any field crop, so field samples of mature cereals, for example, will almost certainly yield mites.
Some mites feed on the seed kernel and on fungi; others are fungivores exclusively, whereas others are predacious or parasitic. Economic loss in store is caused not so much by what the mites eat, as by the damage that results from the changes in the moisture content of the medium which they initiate and the resultant mould growth and taint.

The group which prefers to feed on solid organic material includes Acarus siro, Tyrophagus putrescentiae (Selv.) and Aleuroglyphus ovatus (Troup.). Food material with a moisture content of 20%-30% is preferred, but the mites will thrive on food with a moisture content of 12%-15% (net weight basis).

The second group, which lives almost exclusively on fungi growing on excessively damp substrata, includes Caloglyphus berlesei (Mich.) and Rhizoglyphus echinopus (Pam and Robin).

The maximum temperatures that mites can withstand are perhaps 10°C lower than those for insects. However, mites, and the fungi on which they may feed, are particularly sensitive to ambient relative humidity and to desiccation. The flour mite, Acarus siro, for example, cannot survive below 60% relative humidity. At 60%-70% relative humidity the population remains static or dies out slowly; and the population only increases rapidly at a relative humidity of 75% or above. Rivard (1958, 1959, 1961a, 1961b) has examined the development of Tyrophagus berlesei on Aspergillus cultures at various combinations of temperature and humidity. He finds, for example, that the percentage mortality at the larval stage is 100% at 60% relative humidity (at 25°C), but that mortality falls to 58% at 70% relative humidity (at 25°C). An increase in either temperature or humidity usually accelerates development from egg to adult and reduces the adult life-span.

The role of mites in the development of hot spots in farm-stored grain has been studied by Sinha (1961). In heating oats, a dominant population of Glycyphagus destructor was followed in succession by Tydeus interruptus, Cheyletus eruditus, Acarus siro, Cheletomorpha lepidopterorum, Haemolaelaps casalis and Kleemania sp. The changes in mite population were correlated with the successive invasion by micro-flora, and the sequence noted was Alternaria-Penicillium-Aspergillus spp.-Absidia-Streptomyces spp. There is laboratory evidence (Sinha, 1963a) of specific relations between species of mites and the species of fungi on which they will, or will not, feed and breed. Figure 13 is a diagrammatic representation of ecological relationships between stored-grain mites and seed-borne fungi under Canadian conditions.

Field investigations (Sinha, 1963a) indicates that most of the mites mentioned above are capable of overwintering in small bulk on forms in Canada. Low-temperature laboratory studies showed that T. interruptus and G. destructor survived exposure to minus 18°C for seven days, Haemolaelaps glasgowi for one day and C. berlesie and C. eruditus for one hour.
Nigrospora, Mucor, Fusarium and Alternaria are the field and storage organisms most preferred by mites. Of these, Alternaria is the most common fungus in healthy grain from the time of harvest until after a few years' storage (Machacek et al., 1951, Wallace and Sinha, 1962), as well as having spores which are larger than most other seed-borne fungi. Thus, those species of mite such as Acarus siro, which can do exceptionally well on Alternaria are likely to be the successful pests of the stored products that contain adequate Alternaria. Acarus siro, which also feeds on the grain kernel itself is the only species of mite classified as a major pest of stored-grain and stored grain products throughout the world. The growth and excessive breeding of Acarus siro in grain of over 15% mc are probably due in part to the feeding on the spores and mycelia of Alternaria, as well as to feeding on the grain.

On the general question of stored-crop hygiene, it is perhaps relevant to mention the mesostigmatid mites, important as predators of other mites and as fungivores, but important also as parasites of rats and mice and as scavengers of excrement and grain debris. It is reasonable to assume that rodents and birds carry Haemolaelaps casalis and other mesostigmatid mites, and if these animals are permitted access to grain bulks, then we have a possible source of mite-infestation. For example, Sinha (1963a) reports the presence of H. casalis on several occasions, in the absence of acarid mites on which they would normally prey.

1.5. A BIOLOGICAL SYNOPSIS

For safe storage, biological activity should be at a minimum. Since biological activity will only occur in the presence of adequate moisture, moisture content is the key to safe storage. The effect of moisture content alone on pathogenic organisms (assuming temperature is not a limiting factor) is shown in Figure 14.

Looking at the effect of moisture content and temperature together, limits to the combinations which inhibit the multiplication of damaging organisms are set out in Figure 15.

For positive advice on acceptable storage conditions, one cannot do better than reproduce the criteria set out by Burges and Burrell (1964) and shown in Figure 1. This indicates acceptable combinations of temperature, moisture content and equilibrium humidity for safe storage, and the combinations which may lead to insect and fungal heating and to a fall in germination. Here, safe storage leads to a fall in germination to 95% in 35 weeks.

In the longer-term storage of healthy seed, under conditions which prevent attack by insects or micro-organisms, the problem is ultimately one of senescence. Obviously, the lower the metabolism of the seed, the slower the rate of usage of reserves. This we now know to be associated with low mc and low temperatures. The optimum mc is certainly below 10%, wet-weight basis (40% relative humidity), for cereals. Temperatures a few degrees above 0°C have been employed for cereals storage. Temperatures a few degrees below 0°C have been shown to be advantageous for other seed crops over extended (five-year) storage periods.
CHAPTER 2

PHYSICAL CHARACTERISTICS OF GRAIN BULKS

In bulk cereals, about 40% of the total volume is air space between the grains. In addition to their granular and porous nature, grains in bulk are characterized by a low thermal conductivity and an ability to exchange moisture both with the air within the bulk and with the surrounding air.

2.1 MOISTURE RELATIONSHIPS

In the moisture exchange between grains and their environment, we are primarily concerned with the exchange of "free water" and with surface effects, rather than with the movement of "water of composition", that is, with the moisture contained within the plant cells (Christensen, 1982).

When a colloidal material such as grain takes up moisture, some of the water is relatively loosely held by capillary forces and is said to be absorbed. In addition, some of the water becomes relatively tightly bound, by forces of the polar or valency type, and is said to be adsorbed. Typically we find a strong dipole attraction between water molecules (H-OH) and substances containing hydroxyl (−OH) or organic acid (−COOH) groups.

Because of the binding forces, water taken up by the grain exerts a lower vapour pressure than a free water surface at the same temperature. As the temperature of the grain and its water is raised, so the vapour pressure exerted by its bound water increases, and in a manner similar to the increase of vapour pressure above a free water surface. Changes in the water-vapour pressure (WVP) exerted by the grain are paralleled by those above the free water surface (the saturation water vapour pressure - SWVP) and the vapour pressure of the moist grain relative to that of free water remains much the same, despite variations of temperature. It follows then that the relative humidity (WVP/SWVP x 100%) of intergranular air in equilibrium with the mc of the grain is largely independent of the temperature of the grain. Moisture content is defined on a wet basis by the equation

\[
mc = \frac{\text{Weight of water in a sample}}{\text{Total weight of sample}} \times 100\%
\]

The relative humidity (rh) of intergranular air in equilibrium with the mc of grain, called the equilibrium relative humidity (erh) increases by about 3% rh per 10°C rise in the grain temperature (Pixton and Warburton, 1971). The form of the relation between grain mc and erh is shown in Figure 3. The importance of an erh of 70% in problems of safe storage against mould attack has already been described. Above 70%-75% rh, small increases in ambient rh may induce large increases in grain mc. In many grain-producing areas, rh in the ambient air making contact with the grain may exceed 70% for much of the day throughout much of the year. In these areas, grain will move towards an erh that may prove dangerous unless the store is isolated from the free atmosphere (air-tight storage). In drier climates, where the rh is mostly below 70%, the uptake of moisture from the free atmosphere may not be significant, and loss in weight of the stored product is possible through moisture desorption.
If a uniform bulk of grain becomes subjected to temperature gradients, then WVP differentials also develop. Hygrometric charts or tables (Christensen, 1982) show the effect of a temperature change on rh. The WVP of the free air remains constant despite changes of temperature. For example, at 20°C, rh 64%, the WVP is 1.5 kPa. If the air temperature is raised to 25°C without the addition of further moisture, the WVP remains 1.5 kPa and charts or tables indicate the rh now to be 47%. Using hygrometric charts, the moisture content of the air is more likely to be expressed as the weight of water associated with unit weight of dry air (kg/kg), and this is the factor that remains constant when considering the effect of temperature changes on rh.

If temperature gradients within a bulk are maintained by internal or external heat sources or sinks, then mc gradients will develop in the grain and in the air between the grains. Diffusion (Pixton and Griffiths, 1971) and also the mass transport of air by convection currents within the bulk, will now lead to a redistribution of the moisture within the bulk. The practical consequences may be slight unless the gradients are steep or the commodity is stored for a long period. Difficulties arise chiefly when warm grain comes into close contact with cool surfaces or cool air currents. A common example is the "sweating" or the appearance of surface moisture on warm, bagged grain from a drier, when the bags are placed on a cool and highly conductive floor.

The direct introduction of moisture into a store or bulk, through a damp wall or leaky roof, can obviously initiate fungal as well as possible insect activity. Such local "hot spots", and caking and spoilage of the grain, is obviously different in character from the fungal activity that may be set up throughout the entirety of a bulk when high mcs exist everywhere. The difference in the result on the grain may, however, only be one of time, since the effects of local spoilage and eventually through the bulk. However, Australian experience (Robinson, 1961) shows that the short-term storage of grain in heaps on the ground, prior to removal to silos, is a practical proposition in those parts. The effect of rain on the heaps is to seal the surface, so that most of the rain, in fact, runs off. Showers giving up to 0.01 m do not penetrate more than a few grains deep; and this zone soon dries out without damage to the grain. Komoll (1965) quotes such a heap being subjected to 0.125 m of rain with a relatively small loss at the surface layers only. Practical considerations are that the surface of the heap should be free from indentations which would collect the rain, and that the heap should not be trampled on by men or animals, to avoid the damage to the grain by compression. "Stalagmites" of caked grain have been known to develop from this cause.

2.2 THERMAL PROPERTIES

The transfer of heat through heaped grain is not a simple process. Both radiation and conduction will occur between the grains themselves and between the grains and the inter-granular air. Small-scale convection will take place between adjacent grains, with some larger-scale convection currents through the bulk. Some transfer of heat by the processes of evaporation, condensation and absorption may also occur.
Laboratory measurements have been made of the over-all "thermal conductivity" of grains of various mcs (Mohsenin, 1980) and the results indicate "conductivities" of the order of 0.1 kg. cal. hr⁻¹ m⁻¹ °C⁻¹. In more familiar terms, this implies that a bulk of grain will have thermal insulation characteristics perhaps five or ten times better than a similar bulk of concrete, though its resistance to heat flow will still be less than that of good thermal insulators. The thermal conductivity of bulk grain is such that apparently minor internal sources of heat - for example, the respiration of insects and fungi - can cause serious rises of temperature (Howe, 1962).

Whilst the rate at which heat is transferred within a bulk depends upon the thermal conductivity, the rate at which temperature changes are transferred (the thermal diffusivity) is dependent also upon the thermal capacity of the stacked grain. Typical values for the thermal diffusivities of grain are of the order 0.8 x 10⁻² m²/s (Kerarian and Hall, 1965).

The expressions for the rate at which external temperature changes penetrate a bulk of grain are of the same form as those for the penetration of temperature changes into the ground (Mohsenin, 1980). The latter may be more familiar to meteorologists, and are indicated in standard works such as that of Geiger (1950).

Diurnal and yearly temperature cycles applied to the external surface of a relatively large bulk (all dimensions greater than 10 metres) will be delayed and attenuated as they penetrate the bulk. Daily variations of the order of 10°C will be reduced to 1°C at a depth of about 0.1 m (Kelly 1940). Annual mean temperature ranges of 40°C will be reduced to 1°C at a depth of four metres inside a grain bulk. In addition to a reduction in amplitude, the advancing temperature perturbation is much slowed by the grain. The summer maximum of external temperature will give maximum temperatures at a depth of two metres a month later (Gough et al., 1987a).

2.3 AIR MOVEMENT

Respiration of the grain leads to oxygen uptake and the production of carbon dioxide. In this, it is reinforced and often over-shadowed by the respiration of associated micro-organisms and insects (Christensen, 1982). If there is no air movement through the grain, the only process able to renew the oxygen supply and remove excessive carbon dioxide is that of diffusion. The resistance to diffusion within the bulk is obviously much greater than in still air. The practical consequences are that in the absence of mass air movements, carbon dioxide accumulates considerably. Being heavier than air, at concentrations above a small percentage, carbon dioxide collects in the bottom of a bin or silo. Here, unless the container is air-tight, the carbon dioxide will leak into the free atmosphere.
Barometric pressure changes will cause a bulk to "breathe". The volume of the inter-granular air responds to these pressure changes and, from time to time, fresh air will penetrate the outer layers of a bulk from this cause. If only one surface of the heaped grain - for example, the top - is available for this movement of expansion and contraction, then an external annual pressure range of 95 kPa to 105 kPa might effect an aeration of about the top one-tenth of the bulk. If the air can enter on all sides, the depth of penetration of fresh air is correspondingly reduced.
CHAPTER 3

PREPARATION OF SEED GRAINS FOR STORAGE

3.1 THE HARVEST

Observations in the British Isles demonstrate a response of the standing ear grain to the environment. Actual mcs of 15% to 35% (wet-weight basis) for the standing field crop are fairly typical and the daily range of mc changes in the order of 5%. For example, Arnold et al., (1958) report the measured mc of grain immediately on harvest falling from 25% in the early morning, to 17% for the cut taken in the early evening of the same day. On another occasion, grain mc on harvesting fell from 23% to 19% over a six-hour period after mid-morning. There is no reason to suppose that this response of the mc of the field crop to diurnal changes in the environment is not typical.

Observations such as those of Arnold et al., (1958) and Mitchell (1955) demonstrate a relation between grain mc and the mechanical damage incurred by the grain during combine harvesting. Oats harvested in this way at 16% mc for example, show greater mechanical damage than do oats combined at 23% mc. (Further drying would, of course, be needed for safe storage against mould attack.)

The timing and the method of harvesting and of the subsequent handling of the crop are obviously relevant to possible deterioration in store. Combining, for example, gives no time for field conditioning of the crop between cutting and threshing. It avoids the hazards of partial field drying (i.e. repeated wetting), attack by insects, animals and disease, but may at times mean that an immature crop is taken to avoid shedding. Immature seeds will deteriorate more quickly than mature grains unless treated further, because of their higher mc and because the enzymes they contain are not yet dormant. Where field wilting and ripening of the cut crop are adopted, drying in the swath on a tall stubble is likely to be a quicker process by virtue of improved ventilation than when the crop is bound in sheaves and stacked. There is obviously scope for meteorological comment on the efficiency of local harvest procedures.

In tropical countries where the crop requires to be harvested during the rains, there are major problems of drying. The literature of such countries offers only limited quantitative definitions of the weather of the day that permits or prohibits harvesting, or quantitative relations among the field drying rate of a cut and wilting crop and environmental variables such as sunshine and wind, air moisture content, precipitation or dew. The need for such information is shown by farm management studies, which seek to plan work schedules and the level of investment in manpower and machinery to cope with both peak work loads and the vagaries of the weather from season to season.

3.2 NATURAL DRYING

Drying a hygroscopic material such as grain is primarily concerned with the removal of capillary water, and occasionally free surface water, if the threshed seed has been wetted by rain or dew. In any drying process (in the absence of solar radiation effects) a limit is placed on the final equilibrium moisture content of the material, by the rh of the drying air. At a particular temperature there is a fixed relationship between grain mc and the rh of the surrounding air.
Early investigations into drying theory are represented by the work of Lewis (1921) and Sherwood (1936). These postulate three distinct phases in the drying process under constant drying conditions - that is, when the temperature and moisture content of the drying air remain constant. In the first phase, when the surface of the drying material remains completely wet, evaporation is similar to that from a free liquid surface of constant area, and the drying rate is constant under these stable drying conditions. In the second phase, there is a decrease in the surface area that remains wetted, and the drying rate decreases, being directly proportional to the fraction of the surface that remains wet. When the surface is completely dry, a third phase is recognized. The drying rate again decreases with time and is controlled now by the rate at which water can be transferred from the interior of the kernels to their surfaces. In the practically important range of mc for food grains, it is the third and last phase that is most often relevant. The control mechanism for the internal movement of water is diffusion across the vapour pressure gradients from the interior of the grain to the intergranular air (Troeger and Hukill, 1971). The major factors affecting the drying rate (in the absence of free surface moisture and under constant drying conditions) are found by Hall and Rodriguez-Arias (1958a) to be, in order of importance, first the temperature of the drying air; secondly the initial mc of the grain; and thirdly the rh of the drying air. Constant drying conditions imply a constant saturation vapour deficit at the surface of the grain. If the saturation vapour deficit of the ambient air and of the grain together give some measure of the vapour pressure gradient applied to the grain, then it will be understood that the absolute change in saturation vapour deficit for unit change of temperature (at constant rh) is greater than the change in saturation vapour deficit for unit change of rh (at constant temperature).

Based on the differential equation for diffusion (Fick's Law), Lewis (1921) derived the following expression for drying rate under constant drying conditions.

$$\frac{M - M_e}{M_0 - M_e} = e^{-k \tau}$$

where $M = mc$ (dry weight basis) after time $\tau$ (hours)  
$M_0 = \text{initial mc (dry weight basis)}$  
$M_e = \text{equilibrium mc (dry weight basis)}$  
$k = \text{a rate constant or drying coefficient}$.

However, this expression is a first approximation only. A more detailed examination of the drying process as a function of the mass flow, temperature and mc of the ventilating air, is described in articles such as those by O'Callaghan et al., (1971) and Bakker-Arkema (1984).
Natural drying for longer-term storage is feasible in some parts, and Hall (FAO, 1963) and Muckle and Stirling (1971) show a number of traditional methods. We may distinguish between those methods which make use of sun drying of shallow layers of threshed grains and those which depend on air movement through open sided and raised containers holding unthreshed grain — e.g. cob-maize or sheaves of cereals. The latter method is unsuitable for threshed grain since the resistance offered to air movement by grains in bulk is too great to be overcome by wind pressure (Sheldon et al., 1960). There is naturally a limit to the dimensions of these wind-ventilated containers. The size and tightness of the stacked crop and the orientation of such stacks to the prevailing winds (Anon (1980), Bodholt (1985)) are important.

In any method of drying, too rapid or over-drying should be avoided. Too quick drying causes internal stresses so that, for example, pulses and spices can burst; while in cereals "case-hardening" occurs. Grain can become wrinkled and discoloured. Rain, wetting and drying set up internal stresses which crack the outer casing of grain kernels increasing the percentage of brokens during milling.

A simple type of shallow layer sun drier (the Allgate drier), designed to minimize the introduction of foreign material, be readily portable and permit the produce to be protected from rain, has been produced in Britain for use in the tropics. Bailey and Williamson (1965) imply that the drying rate with this kind of drier is increased if air movement over the surface is restricted by a wind-break. This is in keeping with the findings of Hall and Rodriguez-Arias (1958a) on the importance of air temperature to the drying process.

The maximum temperatures of produce drying in the sun in the tropics, when spread in layers about 0.05 m thick are around 36°C (FAO, 1963). The optimum and lethal temperatures for insects are about 30°C and above 45°C respectively. It is usually not possible to kill all insects or their larval stages by the temperatures reached in solar drying.

3.3 ARTIFICIAL DRYING

Artificial drying involves the forced ventilation of grain, with heated air. Driers in general use today include "Continuous-flow" driers, "Batch" driers, "On-floor" driers and "In-bin" driers. "High-volume" air driers are also used - these use unheated air and the drying operation is called aeration.

Continuous-flow and batch driers will remove water at the rate of 1%-1.5% mc per hour from layers 0.15 m to 0.6 m deep and usually employ drying temperatures of 40°C-60°C. Air velocities through these shallow layers of grain will be of the order of 0.25 m/s. In grain seeds where viability is to be preserved, there are restrictions on the time that the grain may spend at these temperatures. This time is dependent on the mc of the grain. These driers have limitations in that the output of a combine harvester may be more than the drier can handle. In a wet harvest, grain held in bulk for several days before passing through the drier may deteriorate seriously due to respiratory heating. One answer to this is to provide aerated pre-drying bins for storage before drying. If such a system is adopted, the mc and temperature of the grain should be monitored.
On-floor and in-bin driers operate on the same principle. Warm air is introduced into the grain bulk through a series of perforated ducts placed under deep layers of the grain or, in the case of some in-bin systems, through a central vertical duct. With this method, the drier can also be treated as a bulk store and the grain left in it when the drying process is completed. Manufacturers of this kind of equipment will usually state the depths to which particular cereals may be loaded over the ducts. If this depth is exceeded, the overall resistance to air movement increases, with the result that grain adjacent to the ducts is likely to be over-dried in the prolonged blowing necessary to effect the drying of the grain at the top of the bulk. Air temperatures used are much nearer the ambient than those of the continuous flow or batch driers, and the temperature lift may only be a few degrees. The drying is accordingly a slower process and variations in the rh of the ventilating air over periods of the order of 24 hours due to weather changes may be significant. For this reason, it is not unusual for on-floor and in-bin driers to incorporate automatic temperature and humidity controls in the heating unit to prevent the uptake of moisture by the grain from the ventilating air.

"High-volume air" driers are essentially similar to the on-floor and in-bin driers, and typical rates of flow (0.5 to 5.0 cubic metres of air/minute/tonne of grain – depending on grain mc) will include those at which on-floor and in-bin driers would normally operate. Since unheated air is used in the drying process, this will not be as rapid as in the other forms of drier. But the avoidance of heating equipment means that the cost of the drying operation is kept down and that the grain cannot be damaged by over-heating, whilst the large volumes of air employed may mean that the drying is more uniform through the bulk than is the case with other deep-layer driers. The possibility of drying with the high-volume air method obviously depends on the moisture content of the ambient air. Figure 3, for example, indicates that it would be possible to dry wheat at 20% mc by air at 80% rh to a final mc of 16%.

Normally, when in deep layers, the grain dries first around the point of air entry and this dry zone extends progressively in the direction of air movement, displacing drying and damp zones ahead of it.

Drying in bulk or in deep layers is essentially a slow drying system, and the risk of spoilage is present unless there is some balance between the depth of grain, the volume of air flowing through the grain and the temperature and moisture content of the ventilating air. Work such as that of Kreyger (1959), shown in Figure 16, or Burrell and Hyde (1965), shown in Table 3.1, give acceptable combinations of time, temperature and grain mc to preserve the germinative capacity of grain such as barley.

The power required to move air through deep layers of grain increases significantly for air speeds greater than 0.2 m/s – speeds of 0.10 to 0.15 m/s are more usual with on-floor and in-bin systems. The volume of the air moving through the grain determines the drying time. Data such as those shown
TABLE 3.1

PERIOD OF SAFE STORAGE (IN WEEKS) AT
VARIOUS TEMPERATURE AND MOISTURE CONTENTS

<table>
<thead>
<tr>
<th>% moisture content (wet-weight basis)</th>
<th>5°C</th>
<th>8°C</th>
<th>10°C</th>
<th>12°C</th>
<th>15°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>60</td>
<td>45</td>
<td>42</td>
<td>38</td>
<td>32</td>
</tr>
<tr>
<td>16</td>
<td>52</td>
<td>40</td>
<td>36</td>
<td>31</td>
<td>27</td>
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<tr>
<td>17</td>
<td>45</td>
<td>31</td>
<td>27</td>
<td>20</td>
<td>12</td>
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<td>18</td>
<td>40</td>
<td>25</td>
<td>17</td>
<td>13</td>
<td>6</td>
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<td>19</td>
<td>25</td>
<td>15</td>
<td>10</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>20</td>
<td>14</td>
<td>9</td>
<td>6</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>21</td>
<td>9</td>
<td>6</td>
<td>4</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>22</td>
<td>6</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

in Table 3.1 indicate the length of time that grain may be allowed to remain at various combinations of temperature and mc without deterioration. Though moisture may be removed from deep layers of grain at a steady rate - typical values are of the order 0.5% mc per day for the bulk as a whole - the drying within the bulk is not uniform and in on-floor systems for example, the top of the bulk would be the last to dry. In drying, say, from 21% to 16% mc the top of the bulk would remain damp, and would be at risk for a period of about 10 days.

More precise estimates of the drying time in particular cases may be made with the aid of psychrometric tables and charts (Figure 17). If the temperature of the grain is close to that of the incoming ventilating air of which the rh is known, the rh of the air leaving the bulk will be close to the equilibrium of the undried grain. This enables estimates to be made of the uptake of moisture by the ventilating air. Information on the rate of air flow then leads to an estimate of the rate of water removal using the formula

\[ M = p_s \cdot V \cdot WC \]

where \( M \) = rate of water removal (mass per m\(^2\) floor area)

\( p_s \) = density of dry air, taken as 1.25 kg/m\(^3\) at sea level

\( WC \) = change in moisture content of air passing through the grain

\( V \) = volumetric flow rate of ventilating air
Consider, for example, ventilating air at 15°C, 77% rh (corresponding to barley at 16% mc) passing through undried barley at 21% mc (equilibrium relative humidity of 90%). The increase in moisture content of the air leaving the bulk, AC, is 1.4g of water per kg of dry air. At an air-flow, V, of 0.075 m/s, the water removed per day from the grain standing on unit area (1 sq. m.) of floor space is 11.3 kg.

If the depth of grain is 3 m, the weight of grain standing on unit area (1 sq. m.) of floor area is of the order of 2 tonnes. The removal of 11.3 kg of water per day from this weight of grain at 21% mc corresponds to an average rate of removal of 0.5% mc per day.

When dry air passes through deep layers of moist grain we may distinguish dry, drying and unmodified layers. Similarly, after ventilating a deep uniform grain bulk for some time with air at normal ventilation rates and at a temperature other than that of the bulk, we may expect to find zones in which the grain has taken up the temperature of the air, a mixing zone where the grain temperature is in the process of change, and a zone where the initial grain temperature is unchanged. This temperature configuration develops much more rapidly than the corresponding one for moisture.

Morris-Thomas (1962) has developed working relations between drying time (or drying rate) and the rate of air-flow and temperature of the drying air, for shallow, high temperature, batch driers of the form:

\[ G = K \frac{Y^{2.4} R_n^{2.4}}{Z} \]

where
- \( G \) = mass rate of air flow
- \( K \) = constant
- \( Y \) = \( R_a/R_n \approx 1.47 \)
- \( R_a, R_n \) = drying rates for artificially moistened and naturally moist grain respectively
- \( \log Z \) = constant \( \tau \)
- \( \tau \) = temperature lift of the heated (drying) air above the ambient.

Correspondingly simple expressions for the drying of deep layers of moist grain are not possible. Iterative procedures for the computation of temperature and moisture profiles within deep layers of moist grain (considered as a series of shallow layers), as a function of through ventilation, are reported in the work of O'Callaghan, et al., (1971) and Bakker-Arkema (1984).
The ventilation rates that are feasible through deep layers of grain imply that the temperature of the air leaving the bulk will be for many hours (and possibly days), close to the initial temperature of the grain at the top of the bulk. In consequence, it is possible that moisture, taken up by the heated ventilating air on passing through the drying zone, is deposited again near the top of the grain bulk. The ventilating air will take up moisture until it achieves a vapour pressure equal to the initial equilibrium vapour pressure of the moist (undried) grain. From hygrometric tables (provided the temperature of the air leaving the drying zone is known) the dew point of this air can be deduced. The likelihood of the deposition of surface moisture in the bulk beyond the drying zone can also be estimated. A first approximation might be that the air leaving the drying zone has a temperature midway between the temperature of the air entering the bulk and the temperature of the unmodified grain at the top of the bulk. With cool, high mc grain bulks in damp warm weather some initial blowing (and drying) with unheated ambient air, may be advisable before any heat is added to the drying air. In order to move large volumes of air quickly through such bulks, grains depths must be lower than those normally employed in on-floor drying systems.

The immediate effect of warm air entering a cool grain bulk is the deposition of surface moisture if the temperature of the grain is less than the dew point of the incoming air. But as the forced ventilation is continued and the temperature of the grain moves towards that of the ventilating air, the ultimate effect of ventilation on the moisture status of the mass of grain depends solely on the rh of the ventilating air and the initial equilibrium rh of the grain (Gough and McFarlane (1984)).

Figure 17 shows a psychrometric chart with curves relating air temperature, mc and rh. In addition, the position of the erh curves corresponding to wheat at mcs of 12% to 26% are indicated. The effects of forced ventilation can be followed with the help of this diagram. The normal sequence of events in the drying (or mixing) zone is for the grain temperature to change and to approach that of the incoming air. The grain temperature then remains close to but less than that of the incoming air, until humidity equilibrium is reached between the grain and the incoming air. Finally, both temperature and humidity equilibria are achieved; if, for example, air at 21°C, 60% rh (point B) is passed through grain at 10°C and 21% mc (90% equilibrium rh) (point A) the sequence of changes experienced by the grain in the drying zone will be shown by the path A, C, B. The sequence of changes experienced by the air on first entering the unmodified bulk will be shown by the path B, A.
CHAPTER 4

CONDITIONING OF BULK GRAIN DURING STORAGE

4.1 NATURAL VENTILATION

The pressure difference due to the "stack effect" (i.e. temperature induced density differences between the intergranular air and the free atmosphere) may be of the order of 3 Pa. The pressure difference required to induce an airflow with velocities of even a few tens of millimetres per second through a shallow depth (0.3 m) of grain is of a higher magnitude, as is shown by Figure 18. Even if top and bottom vents are provided, the natural ventilation of the grain from this cause will be negligible.

At low wind speeds (less than 2.5 m/s) the pressure exerted by the wind will be of the same order as that due to the stack effect. At moderate wind speeds (about 10 m/s) the pressure due to the wind will be of the order 50 Pa. Pressure differences of this magnitude will induce an acceptable airflow through bins of ear corn (unshelled maize) with depths up to 3 m. But for smaller threshed seed grains, such as wheat or barley, the resistance to airflow is about one hundred times greater than for ear corn, and effective natural ventilation is impractical.

With grain in a bin or silo that is already heating, little is achieved by opening the top, except to prevent damage to the grain top surface from condensation.

There is little difference between the natural ventilation of large bulks and of closely stacked bags. In loosely stacked bags the air is permitted to circulate freely around individual bags of grain and appreciable heat and moisture exchange is possible. A 100 kg bag, with a 20°C temperature difference between the grain and the free atmosphere, will cool as much in 24 hours (by some 15°C) as will a 8 m x 8 m x 8 m stack, under the same conditions in a month. In temperate climates, 18% mc is sometimes regarded as a safe level to store grain in sacks for several weeks, provided that the sacks are not piled more than two deep. Experience has shown that a clean, sound sample of grain of lower mc may be stacked four, or even five sacks deep, provided that sufficient space is left between the ranks to allow a reasonable circulation of air and to ensure that grain temperatures are close to ambient air values.

4.2 FORCED VENTILATION

The passage of air through stored grain can change its temperature and moisture content and can remove odours. Initial drying of a grain bulk and the maintenance of satisfactory storage conditions within the bulk are usually separate operations. Aeration of grain bulks with ambient air (or with air heated only slightly above ambient temperatures), is carried out in a number of countries. The main objectives of such aeration are to:

(a) lower grain temperatures (to cool a mass of warm grain perhaps after drying or harvest at high temperatures);

(b) equalize grain temperatures through the bulk (to control localized heating);
(c) remove unpleasant odours or toxic gases after fumigation; and

(d) reduce moisture content (usually to a limited extent over a protracted period).

The airflow rates adopted (of the order 0.1 cubic metres of air/minute/tonne of grain) are in general less than those used in instore drying of bulk grain. To avoid the possibility of the grain taking up water from the ventilating air, either directly, or through the translocation of moisture, the temperature of the incoming air is normally kept below that of the grain bulk.

The rate of ventilation to remove the heat produced within a bulk can be determined. An extreme figure for the rate of heat production of the dampest grain likely to be placed in bulk is $3.5 \times 10^{-2}$ kg J/m$^3$/s (Oxley 1948). A more normal figure may be $0.4 \times 10^{-2}$ kg J/m$^3$/s. Table 4.1 shows the volumes of air required at various temperature differences between ventilating air and grain to remove heat produced at three different rates.

**TABLE 4.1**

**VOLUME OF AIR PER SECOND PER UNIT VOLUME OF WHEAT NEEDED TO REMOVE ALL THE HEAT PRODUCED**

<table>
<thead>
<tr>
<th>Heat production (kg J/m$^3$/s)</th>
<th>Increase in temperature of the air leaving the grain over that entering</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20°C</td>
</tr>
<tr>
<td>$3.5 \times 10^{-2}$</td>
<td>0.084</td>
</tr>
<tr>
<td>$1.4 \times 10^{-2}$</td>
<td>0.033</td>
</tr>
<tr>
<td>$0.4 \times 10^{-2}$</td>
<td>0.010</td>
</tr>
</tbody>
</table>

An airflow of 0.003 volumes per second per unit volume of grain (approximately 0.0015 cubic metres per second per tonne) corresponds to a velocity of 0.01 metres per second through grain three metres in depth. Such an airflow would usually prevent a temperature rise in grain bulks in temperate climates. Double this airflow rate can produce rapid cooling in a hot tropical climate.
The cooling of dry grain, by ventilation with ambient air, down to temperatures of 16°C or 17°C (at which temperatures insects do not develop readily) provides limited insect control (Burrell, 1967). The alternatives are the use of insecticides or fumigation. The economic use of aeration depends on the local climate, and on the time during which the combination of ambient temperatures and absolute humidities will be suitable for aeration of the grain. By suitable instrumentation — for example, with differential thermostats set to bring fans into operation when the temperature of the outside air is several degrees less than the temperature of the grain — control and cooling of the grain are made automatic. Australian experience of this method is reported in the work of Elder (1967), Griffiths (1967) and Sutherland (1967); British experience is reported by Williamson (1961), Burrell (1967) and Sharp (1984) and American experience by Holman (1957), Rabe (1958) and Bakker-Arkema (1984).

4.3 GRAIN CHILLING

If the climate is such that the ventilation of a dry grain bulk with the ambient air does not lower the grain temperature sufficiently quickly to hold insect infestation in check, then chilling of the ventilating air by refrigeration units may be an economic method (Sutherland, et al., 1970).

Ventilation with mechanically refrigerated air is most usual, however, to give a positive control of mould growth in the damp grain bulks for example in humid tropical regions. The temperature of the grain must be reduced to between 7°C and minus 1°C, depending on its moisture content. At these temperatures, insect population growth and mould growth are controlled but mites will be controlled only if the temperature is below 4°C.

Christensen (1982) reported that chilling was finding an increasing use, both as a short-term measure of control before drying is undertaken and for longer-term storage at temperatures well below that at which the grain is harvested; subsequent reports have not indicated a widespread use of the system.

Often, if the grain is to be prevented from spoiling, chilling must be rapid, and suitably low bulk temperatures must be achieved within a matter of days. Periods of safe storage (see Table 3.1 and Figure 16) are again relevant.

To chill one tonne of grain at 21% mc (wet-weight basis) from 20°C to 5°C requires the removal of 3.2 x 10^7 J. However, whilst the air is being chilled, moisture is usually deposited on the cooling coils, giving up latent heat of condensation. On a warm humid day in the British isles, this latent heat may be such that as much as 8.5 x 10^7 J from one tonne of grain. At night and in cold weather, this load is significantly reduced.

Refrigeration is not straightforward, since cold air, passing through warm, damp grain increases in temperature and carries off moisture, thus cooling the grain by evaporation. The amount of evaporative cooling depends on the temperature and moisture content of the grain and, for example, during the cooling process, possibly one-third of the total temperature drop may be accounted for by the incidental removal of 0.5% mc from the grain.
Once chilled, the grain must be kept cold by further refrigeration. There can be an uptake of heat, particularly within metal silos, from the outside atmosphere. A grain bulk chilled to 5°C at harvest time may, in the British Isles, warm up to over 10°C at a depth of 0.6 m in two weeks. It is found necessary to re-cool the grain frequently, at 10 to 14 day intervals, during hot weather in the British Isles, but rather less frequently, at one to three month intervals during the winter. The importance of the heat conductance of the surfaces that come in contact with bulk grain has been mentioned in connection with the sweating of warm grain. The matter is raised again in the present context. It is found to be comparatively uneconomic to chill damp grain in deep metal bins. The heat gain from the atmosphere is such that the re-cooling of grain at the sides of the silo takes about as long as the initial refrigeration of the bulk. Floor storage will normally afford less opportunity for the penetration of heat through side walls for a given quantity of grain, than will bin storage. In fact, in most situations where air is forced through a grain bulk, it may be advantageous to insulate the silo to prevent the external atmosphere from determining the temperature of the grain next to the walls. For if there is any source or sink of heat which maintains the temperature of the grain at a temperature different from that of the incoming ventilating air, the final effect on the moisture content of the grain remains the same as the initial effect, when the incoming air has its temperature changed to that of the grain. This is because the absolute humidity of the ambient air is usually independent of temperature changes which occur during grain chilling.

4.4 AIR-TIGHT STORAGE

Since in some weather conditions nothing is to be gained and positive harm may result from the exposure of stored grain to the free atmosphere, the deliberate air-tight storage of grain is sometimes adopted. This is not always easy to achieve, but the store then becomes protected against the entry of insects and animals and against the uptake of moisture from the atmosphere. Although gas-tightness is not an essential feature for the storage of grain in cool or temperate climates, it has been considered to be desirable in the tropics and sub-tropics, where, because of higher temperatures, insects develop more quickly, and fumigation of grain stocks is a more common storage routine (Hyde, 1973).

Air-tight storage to control the activities of insects and moulds brought in with grain makes use of the fact that respiration of these organisms results (sometimes within a matter of hours) in the almost complete depletion of the oxygen content of the store. This greatly reduces most metabolic processes, though anaerobic (fermentation) processes will continue if the mc of the grain exceeds 18% to 21% mc (wet-weight basis). The wetter the grain, the more marked this fermentation tends to be. Whereas grain of 18% to 21% mc may change little, except to darken slightly and become softer (it may still be relatively bright and free running after a year in store), grain of 24% mc or above is likely to have a distinct smell reminiscent of brewers' grains and to be subject to sticking or "bridging" in the silo on attempted removal. In fact, the air-tight storage of grain at these high mc's implies that the grain will be used for feeding to livestock, since the method is unsuitable, for example, for wheat intended for milling, or grain intended for seed or for malting. In general, high-moisture grain of 15% to 26% mc can be stored successfully, provided precautions are taken to avoid the entry of appreciable quantities of air in the sealed silo. Exceptionally, grain of 30% to 45% mc has been successfully stored (Burrell, et al., 1978).
Generally, the concentration of oxygen must fall below 2% to control all phases of insect pests, and below 0.2% to inhibit the growth of aerobic moulds and bacteria. Weight for weight, the oxygen consumption by insects is much greater than that of grain, so that the rate of oxygen depletion is increased in the case of infested grain. The minimum oxygen concentration required to ensure survival at the various stages of insect development is not a constant factor, and the minimum concentration necessary to prevent completion of the life cycle and multiplication is that of the most susceptible, rather than that of the most resistant, stage. Work to establish the minimum concentration of oxygen necessary to ensure the survival of two species of storage pests has, for example, been carried out at I.A.R.I., New Delhi, India (Pradhan, 1968), the results of which are reproduced in Table 4.2.

<table>
<thead>
<tr>
<th>Species</th>
<th>Stage</th>
<th>Oxygen content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tribolium castaneum</td>
<td>Fully-grown larvae</td>
<td>6.37%</td>
</tr>
<tr>
<td>Tribolium castaneum</td>
<td>Adults</td>
<td>7.24%</td>
</tr>
<tr>
<td>Trogoderma granarium</td>
<td>Eggs</td>
<td>16.77%</td>
</tr>
<tr>
<td>Trogoderma granarium</td>
<td>First instar larvae</td>
<td>5.35%</td>
</tr>
<tr>
<td>Trogoderma granarium</td>
<td>Fully-grown larvae</td>
<td>1.08%</td>
</tr>
<tr>
<td>Trogoderma granarium</td>
<td>Adults</td>
<td>3.39%</td>
</tr>
</tbody>
</table>

Table 4.2 shows that:

(a) Different stages of the same species have different tolerances to reduced oxygen concentration;

(b) The insects generally die well before the oxygen content of the air (normally 21% by volume) is exhausted (and at oxygen concentrations well above those at which the anaerobic respiration of moulds will become dominant in moist grain);

(c) Absolute air-tightness and the maintenance of very low oxygen concentrations may not be necessary for insect control;

(d) Trogoderma granarium, which can breed at very low grain moisture contents, is nevertheless susceptible to reduced oxygen concentrations.
For air-tight storage, both underground and aboveground structures are employed. There may be little to choose between the two and practical considerations may dictate which one is adopted. Underground structures are subject to smaller fluctuations of the ambient temperature than those aboveground and may, because of the configuration of the bulk of grain they contain, be more resistant to the movement of air through the bulk; aboveground structures are the more convenient for inspection, maintenance and operations such as turning the grain.

Extensive use has been made of underground storage in Argentina, Cyprus and Kenya; for example, cone shaped concrete lined pits with domed concrete roofs are successfully used for storing maize (Gough, 1985). With aboveground silos we may distinguish between air-tight silos having sealed roofs and unloaded at the bottom and the more conventional silo, top unloaded and having only a nominal seal at the top. This might be of polythene sheeting placed over a layer of straw or chopped grass to take up and hold moisture transferred to the grain top surface by convection (Gough, et al., 1987b).

When the silos are opened, there is, some penetration of fresh air. Daily opening of the bottom-unloaded tightly sealed silo does not cause significant spoilage of the grain, if the oxygen introduced is taken up in respiration. A relatively small but continuous air leakage can have serious consequences. The top unloading of the more conventional silo must be sufficient to keep ahead of spoilage; the depth of grain removed on each occasion should at least be close to the depth of penetration of fresh air. This penetration is dependent upon several factors (Banks, 1984) and synoptic changes will predominate. For example if a 24-hour pressure change of 2000 Pa to 2500 Pa covers most situations, then the depth of aeration from this cause should not exceed 1/50 to 1/40 of the total depth of the bulk of the grain. All air-tight silos should have some means of relieving pressure differences between the silo and the outside atmosphere. There are at least three commercially available systems which do this. The first makes use of a "breather" bag within the silo, together with an overriding pressure-vacuum relief valve. If the pressure inside the silo becomes less than that outside, air passes into the bag; conversely, air is expelled from the breather bag when the external pressure falls relative to that in the silo. The relief valve comes into operation if the capacity of the bag is exceeded due to extreme synoptic changes, the removal of large amounts of grain at one time, or to excessive respiration. A second system makes use of gas storage cells connected in series with the silo. A third makes use of pressure-vacuum relief valves alone to effect an exchange between the outside air and the silo gas in the roof of the store.

Gas-tightness in the storage of moist grain is more critical than in dry grain in controlling insect attack. Regarding the latter, reference should be made to the storage bin (Pusa Bin) developed at I.A.R.I., New Delhi, in which a gas seal, consisting of a thin sheet of polythene film (0.175 mm thick) is sandwiched between the mud walls of an ordinary earthen structure. Enclosing the polythene within the walls protects it from mechanical damage. The structure is effectively impervious to water vapour and atmospheric oxygen; and the thermal insulation is sufficiently good to reduce the dangers
of significant moisture transfer to the walls. Figure 19 shows the construction of the Pusa Bin. The earth layers may be replaced by any other suitable material of poor thermal conductivity (wood, of course, is subject to attack by termites) and the size of the storage structure which could use such a gas seal is presumably limited only by normal building considerations.

Comparative tests demonstrate that freshly harvested wheat in India may be kept safely in such a structure. None of the four common storage pests — viz., *Sitophilus oryzae*, *Rhizopertha dominica*, *Trogoderma granarium*, *Tribolium castaneum* — breed well, even when deliberately introduced, provided the initial moisture content of the wheat is 10% or less. The viability of seed wheat was unimpaired after storage for more than three years.

Inflatable plastic buildings, particularly when fitted with a floor and so designed that they can be made gas-tight, become suitable for the storage of cereals and are termed "air warehouses". These stores can meet the demand for buildings that are portable, do not require expensive foundations, are weather-tight and proof against the entry of water vapour and insects. They facilitate insect control by fumigation, and the waterproofed floor prevents the uptake of moisture from the ground. The plastic sheeting used must be carefully chosen as there is evidence (Gough, 1979 and Gough, 1982) that some plastics and rubbers are degraded when exposed to tropical climates, particularly if they are stressed.

Such buildings may need a considerable amount of management (O'Dowd and Kenneford, 1983). An air warehouse in Kenya, for example, loaded with some 40,000 bags of paddy and then allowed to deflate, was stored for an average period of six months with a loss of less than 0.4% of the total input. This loss occurred mainly in the hot season, when night-time ambient cooling led to condensation of the moisture that was taken up by the air from the paddy (Griffiths (1984), Gough and Locke, (1984)). This hazard was alleviated to some extent by inflating and then deflating the warehouse daily (that is, by ventilating the store). In the cold season, there was some translocation of water vapour downwards. This damaged peripheral bags of the lowest layers. Presumably, the stack maintained the initial temperature of the ground beneath it, whilst the temperature of the soil around the stack was able to fall, thus permitting non-isothermal moisture diffusion (Thorpe 1982).

Attempts to make conventional rigid structures airtight were found to be difficult to achieve in practice. The principal source of gas leakage is wind which induces pressure differentials across the storage structure (Banks et al., 1983). Recent studies (Banks and Annis, 1977, Gough and Locke (1984)) suggest that grain at 14% mc can be successfully stored in a nitrogen or carbon dioxide atmosphere. Carbon dioxide has the added advantage of being a fungistat.
CHAPTER 5

INSTRUMENTS AND MONITORING OF GRAIN BULKS

5.1 LABORATORY MEASUREMENT OF MOISTURE

A number of methods are available (e.g. International Standards Organisation (ISO) Reference Method, R712 (1985)) which normally provide the reference standards for moisture meters under field conditions. In general, a sample of the grain has to be taken from the bulk. The sample should be representative of the parcel of grain being examined, and be kept in an airtight container.

In one type of reference method, the oven-drying method, moisture content is found from the loss in weight of ground grain exposed to a forced-air draught at a nominated temperature for a specified time. Accuracy is better than ± 0.1% mc.

The distillation reference method (e.g. ISO R939) is frequently used for produce that easily breaks down chemically when heated or which contains low molecular weight constituents. A weighed sample is heated in for example toluene and at a fixed temperature slightly in excess of the boiling point of water. The water driven off is collected, together with other volatile, immiscible products, and condensed into a graduated container. The variation of the temperature of the boiling point with pressure may give rise to apparently inconsistent results at places which differ considerably in altitude. The sample is heated until further weight change is considered negligible.

A "rapid" laboratory method (20 minutes) in which an infra-red lamp is used to heat a weighed sample on a balance pan, for a fixed time, gives results with an accuracy of about ± 0.3% mc.

5.2 FIELD MEASUREMENT OF MOISTURE

Electrical methods now make use of the variation of electrical resistance or capacitance of the grain with mc, and determine the mc of the grain indirectly (Mackay, 1967)

The electrical-resistance instruments usually either require the grain to be crushed of milled in a small compression cell where a standard, predetermined pressure is then applied. Resistance across the sample is measured. A correction for temperature is necessary, and in meters of modern design this takes place automatically.

Capacitance meters respond to changes in the capacitance of a cell containing the sample. Two parts of the cell effectively form the plates of an electrical capacitor. These meters are sensitive to the packing configuration of the grains in the cell. A correction for temperature is again required, which is automatically included in modern moisture meters.
The hair hygrometer (Gough, 1974) is also used to measure the humidity of the intergranular air of a grain bulk or bag stack and so, indirectly, to obtain a measure of the mc of the grain. Expansion or contraction of the hair with a change in the surrounding rh is transferred, through a mechanical linkage, to a dial reading. Up to 20 minutes is required before the hygrometer comes into equilibrium with its surroundings.

Though manufacturers may claim accuracies of ± 0.5% mc for their instruments, tests have shown that accuracy varied between types of instrument and within any one type of instrument. These instruments showed greater variability than the infra-red lamp and, taking capacitance, resistance and hair-hygrometer instruments together, Stephens and Hughes (1966) found that only 45% to 60% of the readings were within ± 0.5% mc of the true value. With individual hair-hygrometers, as few as 20% of the readings were within ± 0.5% mc of the true value. Apart from errors inherent in these instruments or their calibration, allowance should be made for the variety of grain being tested. A separate calibration is desirable for hard and soft varieties of wheat and hard and soft varieties of maize, where real differences of the order 1% mc could arise under the same ambient conditions. Broadly, a difference of 1% mc equates with a difference of 4% to 5% in erh. It is important to calibrate moisture meters against a standard mc determination (Gough, 1983; Gough, 1988).

5.3 MONITORING TEMPERATURE AND MOISTURE

Technically, the monitoring of temperatures within a bulk is not difficult. Remote-reading thermistors, thermocouples and platinum resistance thermometers have all been inserted into grain stacks and silos as the mass of grain is being built up (Muir 1970; Gough et al., 1987(a)). Small numbers of embedded instruments do not necessarily give early warning of local spoilage and temperature rise. For this reason, portable probes, used at regular intervals can be more effective than fixed equipment which could induce a false sense of security. Some allowance must be made for the time lag of the portable instrument inserted and the possibility, for example, of a metal probe falsifying readings by conducting heat away from the sensing head. A limitation of probes is that about a two-metre length is usually the largest a manufacturer will offer and it is difficult to insert probes more than one metre particularly in unhusked grains e.g. paddy rice. One or two metres may not be long enough to reach potential trouble spots in large masses of stored produce. Temperature sensors e.g. thermistors have been inserted into bulks through polythene tubes, after the manner of soil thermometers or as probes when simply taped to sticks.

The practical problems that occur with any method of obtaining temperature readings from within grain bulks, together with the problem of interpretation of the readings taken, suggest that the method adopted may depend largely on local circumstance or preference. A detailed description of the methods of temperature measurement in storage is published elsewhere (Gough, 1974).
Moisture content can be measured remotely at any place in a storage system using Reethorpe Moisture Monitors. These devices along with other methods of remote moisture measurement are described elsewhere (Gough 1974). The monitor performance in a particular application is discussed in "Evaluation of a remote moisture sensor for bulk grain" by Gough (1980).

Management of a grain store should certainly take into account a possible error in temperature and moisture indications. It is inadvisable to assume that a limited number of temperature and/or moisture sensors linked to an automatic warning device or ventilation fans will ensure safety particularly if quality control at intake is unreliable. Where ventilation equipment is installed in or under the grain, it is probably safer to use it briefly at intervals even if sensors do not indicate significant changes.

Some guidance can be offered on the places within a grain bulk to monitor most closely for indications of temperature and mc increases (Griffiths, 1964; Gough, et al., 1987(a)). These would obviously include places where dust and dockage may have gathered—for example, under an outlet spout of a conveyor, and at a grain bulk top surface and at a silo wall where weather conditions may induce mc increases by air convection and non-isothermal moisture diffusion respectively (Uiso, 1985 (private communication), Gough et al., 1987(b)). In a conventional on-floor store it would be sensible to remember where the wettest parcels of grain had been put, and to monitor well down into the heap at places where the drying air stream may have been least effective—e.g., midway between air ducts or, in the case of single-duct systems, at the bottom corners, at the shoulders of the heap and where the grain is deepest.

Aside from the local variations of temperature and mc that will remain within a bulk after first drying for storage, there are the changes that may be induced subsequently by mass convection currents within the bulk (Gough, et al., 1987(b)). Grain in a tall bin at a higher temperature than the mean ambient air temperature will cool at the sides and at the top, and this will give rise to air movements and the translocation of moisture within the bulk (Figure 20). The migration of moisture from this cause can, of course, occur no matter how far the grain has been dried. Grain in a flat bulk at a higher temperature than the ground and the surrounding air will behave similarly. The regions most likely to be subject to the takeup of moisture in these situations are described elsewhere (Gough, et al., 1987(a)).

The Reethorpe Moisture Monitor is the only simple, indicating sensor for grain mc (or rh of the intergranular air) that is also reliable, stable, accurate and comparatively inexpensive (Gough, 1980). Spear probes will enable grain samples to be taken from a bulk for mc determination. Hair hygrometers are available as are probe instruments. Electronic hygrometer probes tend not to be used for remote rh measurement because of their high cost and tendency to drift away from calibration after a few weeks. Being installed in the bulk during filling, they cannot be removed for recalibration (Gough, 1974).
5.4 AERATION

If the grain is in a ventilated silo, then a check on the condition of the grain is possible by blowing air through the bin at regular (weekly) intervals. The temperature difference of the air between entering and leaving the bulk will give some indication of the extent of grain heating.

The resistance to airflow through a grain bulk is a function of its depth, bulk density (which depends on the mc and degree of packing), the type of grain and extent of impurities present - for example, the amount of dust, weed seed or straw. Information is available in the literature (e.g. Osborne (1961), Shed, 1952; Sheldon et al., 1960) on the relationship between airflow and static air pressure applied across a bulk of grain. A measurement of static pressure will give some indication of the probable airflow through a bulk, but if a direct measurement of airflow is required, then instruments to measure low air speeds (of the order of 0.1 m/s) become necessary. Instruments of the heated thermistor bead type can be used but a simple glass tube containing a soap film with its central axis along the central axis of the tube is potentially more accurate (Burrell, 1967). The glass tube is connected to a metal tube, of the same diameter, which is pushed vertically into the top of the bulk being ventilated, and surveys across the top of the bulk are readily made. It is unlikely that ducting can always be arranged to give a uniform airflow through all parts of a bulk, and extra ventilation time will be needed to accommodate those parts of a bulk where the airflow is least (Burrell, 1967).

Control equipment for the automatic aeration of grain bulks is a subject that has been widely studied (e.g. Navarro and Calderon, 1982). As has been stressed already, the movement of air through grain is only desirable if the net effect is to cool and/or dry the grain. In general, the temperature and relative humidity of the outside air will need to be considered together, rather than in isolation (Gough and McFarlane, 1984), and the effectiveness of a control system based on only one of these variables is obviously highly dependent on local conditions, both of local climate and of the state of the grain going into store (Sharp 1984). Systems developed in one region will not necessarily be of direct application elsewhere. Another practical point is that the control system that would appear to offer the best theoretical advantages may fail down on technical or economic grounds.

Control systems include manually adjusted temperature difference controllers, the thermostats being reset after each period of blowing initiated by certain maximum temperature differences between the grain and the outside air. Overriding time clocks have also been incorporated with this type of system. These would exclude aeration during the hours when the diurnal variation of the ambient rh would normally lead to an increase in grain mc.
Fully automatic systems have been based on aeration initiated by time clocks alone, by automatic temperature difference controllers and by adaptive controllers which call for fan operation whenever this would result in an improvement of the grain temperature profile, as measured by sensors on a cable suspended in the grain. Sutherland (1967) reports computer simulation trials at various airflow rates, with systems such as these. The most effective performance was suggested to be given by the adaptive controller. The least effective control was given by time clocks.

Estimates, based on ambient air temperatures alone, of the number of hours during which aeration will be possible, have to be revised downwards when hours with excessive rh are excluded. Where the normal practice has been to set controls to some minimum temperature difference between the grain and the ambient air and to provide an overriding humidistat, an increase in the hours of fan operation can be achieved if the humidistat is removed, or if the external sensors are replaced by one operating on wet-bulb temperature. Whether such a system is practicable and whether safe grain mcs are likely to be retained must be a subject for local study. Certainly, in parts of Australia, where high grain and ambient air temperatures at harvest make aeration important for containing insect infestation, wet-bulb control of the aeration of the low-moisture grain seems a feasible proposition (Griffiths, 1967), though the requirement for maintenance-free, self-regulating controllers may rule out the use of wet bulbs in many instances (Bakker-Arkema, 1984).
CHAPTER 6

GRAIN STORAGE AND THE METEOROLOGIST

6.1 THE GRAIN STORE

For safe storage, grain has to be kept cool and dry. These requirements must obviously be reflected both in the siting and characteristics of the building or structure housing the grain. Heat uptake from the environment has to be reduced and heat loss from the store to the environment has to be increased to achieve an economic optimum. At the same time, the moisture exchange between the grain and the external environment should in general be such as to reduce the moisture content (mc) of the grain (though we have seen that in the cooling of hot, dry grain to prevent insect infestation, some increase in mc may be acceptable).

Where there is some choice in the siting of a store, or of its design, or of the materials to be used in its construction, then the meteorologist can suggest points which perhaps the farmer or builder might consider. This note sets out to cover a range of climates, thus only generalizations are possible. One can at present only draw attention to factors which will influence the temperature and moisture status of the grain, leaving the implications to be worked out locally.

A mathematical model of the heat and moisture transfer processes in stored grain, induced by climate is necessary to estimate the important changes. The drawing up of heat and moisture balances recommends itself. In practice it is difficult to measure a moisture balance. This is because the climate tends to induce the largest changes at the grain bulk or bagstack surfaces: this is easy to measure but the corresponding depletion of moisture within the bulk or stack is not usually detectable (Gough, 1985).

6.2 HEAT BALANCE EQUATIONS

Moisture balance is not attempted here but an approach to the heat balance between a bagged grain store and its environment is suggested by O'Dowd and Dobie (1983) and in the CIBS guide (1979). In grain stores which have few windows, the heat gain, $Q_f$, consists of gain through the fabric, $Q_f$ and gain through ventilation, $Q_v$, so that $Q_f = Q_f + Q_v$.

$Q_f$ is the sum of the products of component areas of the fabric $A$, the thermal transmittance $U$ of the fabric and the difference between the sol-air temperature $t_{ea}$ and the internal environmental temperature $t_{ei}$ (Petherbridge 1974) such that

$$Q_f = AU (t_{ea} - t_{ei})$$

$Q_v$ is the product of the ventilation conductance $C_v$ and the external and internal air temperatures $t_{e0}$ and $t_{i0}$ so that

$$Q_v = C_v (t_{e0} - t_{i0})$$

and therefore

$$Q_f = AU (t_{ea} - t_{ei}) + C_v (t_{e0} - t_{i0})$$
For steady state conditions, when grain temperatures approximate to mean in-store temperatures

$$Q_t = 0 = AU (t_{eo}' - t_{e1}') + C_v (t_{eo}' - t_{e1}')$$

(1)

where the dashes refer to mean 24h values. The mean sol-air temperature $t_{eo}'$ is that temperature that would cause the same quantity of heat flow as the solar radiation causes to flow at a surface. This value, the sol-air temperature, is expressed as the mean 24h sol-air temperature:

$$t_{eo}' = t_{eo}' + R_{so} (\alpha I_i' - eI_L)$$

(2)

where

- $t_{eo}'$ = mean 24h external air temperature °C
- $R_{so}$ = surface resistance in m² °C W⁻¹. Surface resistances are lower for severely exposed surfaces, higher for sheltered surfaces. Surface resistance also varies with the emissivity of the surface.
- $\alpha$ = absorption coefficient, ranging from 0.2 for clean white surfaces to 0.9 for dirty dark surfaces.
- $I_i'$ = the intensity of total solar radiation on the outer surfaces in Wm⁻², including direct and diffuse radiation, expressed as a 24h average.
- $e$ = emissivity of the outer surface to long wave radiation.
- $I_L$ = the intensity of long wave radiation from a black surface at air temperature Wm⁻². The product eI_L is usually zero for walls. (For roofs eI_L varies from 5 Wm⁻² for polished metal to 90 Wm⁻² for untreated surfaces (Petherbridge, 1974)).

Substituting equation (2) in equation (1) and assuming that the mean internal air temperature $t_{e1}'$, in the store gives:

$$0 = AU(t_{eo}'-t_{e1}') + AUR_{so} (\alpha I_i' - eI_L) + C_v (t_{eo}'-t_{e1}')$$

Simplifying, for the steady state condition and employing $g$ to include all store surfaces:

$$t_{g}' = t_{e1}' = t_{eo}' + \frac{\sum AUR_{so} (\alpha I_i' - eI_L)}{\sum AU + C_v}$$

(3)

$C_v = 0.33 Nv$ where $v$ is the volume of the building and $N$ is the number of air changes per hour (ach), for low ventilation rates.
N is approximately 1 to 2 ach for a store with its ventilators closed.

It is assumed that in the steady state condition the average grain temperature $t'_g$ will be equal to the average store environmental temperature $t'_{e_1}$ and therefore the effect of grain is not included in equation (3). In reality the intensity of solar radiation ($I_s$) and the value of the external temperature $t_{e_0}$ both vary through the day; therefore these swings affect the grain temperature. The swings in heat flow can be expressed, for conditions external and internal to the store for equilibrium; using the tilde sign, $\tilde{\nu}$

$$\tilde{Q}_x = \tilde{Q}_1$$

where $\tilde{Q}_x$ = the swing in heat flow caused by external conditions

$\tilde{Q}_1$ = " " " " " affecting the internal conditions.

The swing signifies the change in a quantity from its mean to its maximum value. The swing in heat flows into the building caused by external conditions $Q_x$ is made up of the swing in structural gain added to the heat gain from swing in outside temperature, i.e.

$$\tilde{Q}_x = \sum f AU (t_{e_0} - t_{e_0}') + C_v \tilde{t}_{e_0}$$

where

$f$ = the 'decrement' factor dependent on the type and thickness of the wall and roof. For concrete 50 mm thick, $f = 0.97$; for concrete 300 mm thick $f = 0.22$.

$\tilde{t}_{e_0}$ = the peak sol-air temperature ($^\circ$C) calculated from equation (2).

The effect of grain in store is included when calculating the swings in heat flow connected with internal conditions in the building, namely:

(i) the ability to store or release energy during the day. This is known as the admittance ($Y$). There are no admittance values for grain and so we include

(ii) the ability of the grain to store or release energy during the day

$$= \frac{1}{2}$$

the weight of grain affected by temperature change x specific heat

time lag assumed for grain to reach swing temperature

(iii) the ventilation conductance $C_v$. 
Therefore using the same notation

\[ \bar{Q}_t = \left( \sum AY + \frac{1}{2} \frac{kK}{W} + C_v \right) \bar{t}_{e_1} \]  \hspace{1cm} (6)

(see O’Dowd and Dobie, 1983).

Combining equations (5) and (6) we have, using the same procedure as before:

\[ \bar{t}_g = \bar{t}_{e_1} = \frac{\left( \sum fA_{U} + C_v \right) \bar{t}_{e_0} + \sum fA_{U} R_{e_0} (aI'_t - eI_L)}{\sum AY + \frac{kK}{2W} + C_v} \]  \hspace{1cm} (7)

where

- \( \bar{t}_{e_1} \) = the swing in in-store temperature (°C)
- \( \bar{t}_g \) = the swing in grain temperature at the outermost layers (°C)
- \( \bar{t}_{e_0} \) = the swing in outside temperature (°C)
- \( f \) = decrement factor for each surface not including the floor because this is not subject to solar radiation, etc.
- \( Y \) = admittance factor for each surface including the floor (Wm\(^{-2}\)°C)
- \( K \) = weight of seed affected by the swing (kg)
- \( k \) = specific heat of the grain, for a given moisture content (J°C\(^{-1}\)kg\(^{-1}\))
- \( W \) = time lag assumed for surface layer of grain to reach swing temperature (s)
- \( I'_t \) = total solar radiation swing for each surface (Wm\(^{-2}\))

\( I'_t \) can be calculated for any latitude and this calculation is included in the ODNRI computer programme (O’Dowd and Dobie, 1983).

Equation (3) shows that mean (24h) in-store temperature and mean (24h) grain temperature will always be higher than the mean (24h) outside or ambient temperature by an amount which is influenced by several factors:
(i) The 'U' value or transmittance (often referred to as the insulation) can vary from 5.0 Wm$^{-2}$ °C and above for sheet metal cladding to 0.5 and below for plastic foam insulation.

(ii) The 'U' value is combined with the $R_{so}$ and a values to reduce the effect of solar radiation. The designer should therefore choose materials which not only have low 'U' values but also have low absorptivities. If possible he should avoid a very sheltered site where $R_{so}$ values will be high.

(iii) He should ensure that $C_v$, the ventilation conductance, is high. This can be done by ensuring that there are large ventilators and by siting the building in an exposed position with the long walls facing the prevailing wind. There is no simple connection between ventilation rate and wind speed but O'Dowd and Bisbrow (1985) found that even mild wind speeds of 1 to 4 m/s give rise to ventilation rates of 2 to 5 air changes per hour for a storage building with large eaves ventilators which was in an unsheltered position.

Equation (7) shows that unwanted temperature swings are caused by

(a) Wide ambient temperature swings combined with high decrement-transmittance combinations, for example, thin cladding which is also a poor insulator, like corrugated galvanised steel sheet.

(b) The combination of high decrement, high transmittance and high absorptivity cladding in conjunction with high solar radiation swing.

The equation also indicates that these temperature swings are reduced by

(c) High admittance values for cladding material, for example concrete block walls.

(d) Low transmittance and absorptivity for cladding materials.

(e) Large areas and volumes of grain, although these will reduce the volume of each air change. Ventilation appears neutral with regard to temperature swings.

From this heat balance analysis it is clear that the grain store designer can reduce the in-store and grain temperature swings by store design, by choice of materials and choice of site.

O'Dowd and Dobie (1983) show how store design and choice of building material are possible in economic terms for a seed store.
In the selection of a site, the preference would naturally be given to one that is well drained, with a low water table and where the effects of runoff and flash storms of high intensity rainfall would be minimal. Soil characteristics other than drainage may also be relevant. In places, for example, one finds "heaving" soils of unstable clay. Stores built on these soils alter the natural ground-moisture equilibrium. The migration of water into clay under the store leads to this clay swelling. It may be sufficient to force up the centre of the floor of the store, with consequent cracking of the walls. (The way is than open for the entry of rain and pests.) These effects would be emphasized in areas where there is a general deficiency of rainfall and a low water table at one season of the year.

The addition of substantial overhangs to prevent the entry of driving rain at, say, the eaves, is not necessarily a simple construction. The wind-loading on such parts, due to rapid fluctuations in the wind flowing over and around the building, may be many times greater than the loading on the roof due to the mean wind pressure (itself a function of the pitch and overall dimensions). Special precautions in attaching such an overhang are likely to be needed.

Damp-proof courses, cavity-wall construction and pitched roofs are not necessarily common to all parts of the world. In the rare instance that average internal store temperatures are lower than mean external temperatures, with temperature differences maintained between the inside and the outside of a store, moisture may condense within the pores of a masonry wall and eventually reach the interior. Even with cavity walls, moisture may distill over from a hot exterior to a cooler interior wall. Condensation from the air within the body of a store (not that within the grain bulk) is countered by additional insulation or additional ventilation. Smith (1964) gives an expression for the temperature of an internal wall (or roof) in terms of the temperature difference of the internal and external air and the insulation characteristics of the wall. If some estimate is available of the temperature and moisture content of the internal air, then the possibility of condensation or the supplementary insulation needed to avoid condensation can be examined.

In regions such as the warm, wet tropics and sub-tropics, biological activity is at a maximum and ventilation of the store at the prevailing levels of temperature and humidity is not an effective method of control. In such regions, air-tight stores, or at least stores that can readily be sealed for fumigation may be considered. Airtight stores exposed to solar radiation will become very hot without natural or mechanical ventilation.

6.3  THE FIELD CROP

In this section it is perhaps more a question of suggesting areas and methods of study than of reporting a positive success and working systems.

The weather of the growing season and the harvest period has a bearing on storage potential. If a mature, well-ripened crop can be gathered, the prospects for satisfactory storage are obviously better than for an immature crop, of high moisture content and low initial viability.
The season, as it has affected the development of insect pests and plant disease, will also be reflected in the initial biological state of the grain going into store. (The extremes of winter may also be relevant to residual insect infestation in stores used annually and not adequately cleaned. This is particularly true in large stores containing large grain bulks (Gough et al., 1987).

Areas for collaboration between the meteorologist, plant pathologist and entomologist in the study of damage to field crops are set out in papers such as those of Schein (1966) and Gillham (1966).

What we now know, for example, about the build-up of certain plant diseases suggests that a single assessment of the effects by the end of the growing season is unlikely to show much correlation with a single weather factor spanning the season as a whole, or with monthly mean data, or even necessarily with local weather observations made once a day. The detail and time interval between weather, field and phenological observations has to bear some sensible relation to the time-scale of the physical processes involved in, or necessary for, the attainment of successive phases in the life cycle of the pathogen. The weather-sensitive phases of the life cycle have to be identified and weather criteria developed which specify necessary and sufficient conditions for these sensitive phases to prosper. The ramifications of this kind of study may be great. They may require the help of a local soil scientist or an examination of the windborne spread of disease from source regions perhaps thousands of miles away. The time-scale of such studies may have to be measured in years rather than months, though this in itself is no reason for not beginning. The observational requirements placed on the meteorologist may be simpler than those for persons with whom he is collaborating, but the final stage, of passing from the detailed observations necessary for weather disease correlations to a predictive system based on a macroscale, synoptic network, is not necessarily simple or straightforward.

Whether one is discussing damage to the field crop by insects (or insect vectors) or by disease, the value of a system which forecasts the severity of attack is greatest in regions where the variation of damage from year to year is greatest. In regions where the problems are pandemic, presumably preventive measures can be taken as routine (if the economics of the situation allow this). Where there is a carry-over of foci of potential damage from crop to crop and the population build-up is a reflection of the vagaries of the weather of the season, Hurst (1965) has shown what may be possible. Obviously, this kind of study would appear more applicable to middle latitudes than to the tropics and sub-tropics.

The weather of the harvest period will determine the initial physical state of the grain - its temperature and mc. Moisture content and the methods of harvest and handling will influence the level of mechanical damage the grain sustains.
The field operations necessary between seed time and harvest affect crop production and subsequent safety in storage. Conventional meteorological forecasts and warnings have a part to play in helping the farmer in his day-to-day decisions. It may be a reasonable inference that the average farmer is capable of interpreting the conventional weather forecast for the next 12 to 24 hours in the light of his intended field operations and the known state of his crop and ground. It may be no more than an act of faith that the average farmer can make use of the more general statements of the extended weather forecast. There are two reasons; first, the need for quantitative statements does not diminish as the period of the forecast is extended; meaningful parameters such as raindays or rainfall amounts are needed rather than some indication of the future location of features on a synoptic weather map. Secondly, given meaningful meteorological parameters, the precise relationship between these and the possibility or advisability of field work may only be readily available to the agricultural advisory (extension) service.

An essential preliminary for agrometeorological forecasts is collaboration between the farmer and the meteorologist to determine weather criteria which fit the decision that particular field operations are now possible. In this manner, the experience of the farmer becomes quantified; and at the same time, the way is opened for the interpretation of past weather records as records of the occasions when such work was possible in previous years. The long-term weather records can now become management aids for longer-term planning.

Cumulative distributions, covering many past seasons, of the days suitable for a particular field operation will give the probability of a given number of such days being available over the seasons to come. Following Duckham (1964), contingency tables may be drawn up in which weather alternates and their frequency of occurrence are set against alternative husbandry practice or farming systems. The probable return on the levels of investment necessary under each combination of circumstances may then be estimated, say, for a 10-year sample period. Agrometeorological data used in this way give a rational basis for decision.

With weather criteria available on the build-up of pests and disease and for the field operations necessary to grow and gather in the crop, climatic surveys should enable some assessment of the relative advantages of different sites and of the probable effects of changes in husbandry techniques or crop varieties.

6.4 THE STORED CROP

In the post-harvest treatment of grain for safe storage, there will in many cases be some initial requirement to dry the grain and/or to cool it and subsequently to maintain low temperatures and/or moisture throughout the bulk. As we have seen, there is a variety of practical systems for doing this, but a common factor to many of them is the forced ventilation of the grain bulk. The starting point in any feasibility study or in plant design must often be the temperature and moisture characteristics of the bulk and the ambient air.
Where past weather records are available in sufficient detail (hourly or three-hourly values are probably required) over a sufficient period of time, simulation studies of the temperature and mc of the stored grain, following on ventilation, can be carried out by computer (Sharp, 1984). Such sophisticated techniques are not likely to be available to many; the problem then becomes one of extracting working information for specific projects or climate surveys by hand methods from more limited data.

Immediately one runs into practical difficulties. Past weather records already processed will almost invariably treat individual parameters in isolation. Data on mean temperatures or mean relative humidity are likely to be readily available, but not so contingency tables, which set out the frequency of occurrence, within various ranges, of combinations of two meteorological elements. Yet this is the preferred form for the estimates necessary for many environmental engineering problems. Obviously, user interests have yet to make themselves felt. Another difficulty is that whereas rh rather than any other measure of mc, is of direct relevance to storage problems, this particular parameter does not easily lend itself to accurate measurement or mathematical manipulation. Very often, recourse to the original observations, rather than to data already processed, will be the only way of obtaining the required frequency distributions.

A method for estimating the frequency distribution of hourly air temperatures from long-period, monthly averages has been given by Shellard and Sarson (1962). Procedures such as this can give an estimate of the number of hours when the outside air temperature will be above or below nominated values and a first approximation to the time during which the unmodified outside air will be suitable for cooling the grain stores.

A second approximation would make allowance for the possibility of high rh prohibiting ventilation for part of this time. Strict estimates of the time when the rh of the ventilating air may be a limiting factor may not be justified, for the Shellard and Sarson procedure leads only to the average number of hours each month when ventilation may be possible. Departures from this average will occur in any given year, due to the vagaries of the seasons and especially the temperature of the grain to be ventilated. The cumulative frequency approach is needed (from the time available for ventilation in a given month from a sample of seasons) before the probability of nominated departures from the average can be discussed.

Comments on the periods necessary to build up reliable climatic normals and, by inference, the periods necessary to build up stable frequency distributions and estimates of departure of a given magnitude from the normal, are contained in WMO Technical Note No. 84 (WMO, 1967). This Note also makes reference to "adjusted normals" based on short period samples of data, but extended on the basis of longer-term neighbouring stations. Comment is also made on the areal representativeness of normals.
A procedure for the delineation of climatic regions potentially favourable for the development of stored-product insects and mites has been given by Sinha (1963b, 1964, 1967, 1968). Observation of the grain temperature at various depths in a typical store was used to obtain a measure of the departure of the grain temperature from the long-period (normally 30-year) mean monthly air temperature on the site. Assuming the derived relation held in similar stores elsewhere, it was then possible to estimate grain temperatures from more readily available climate data. The suitability of an area for the development of the major species of insects followed from the work of Howe and Lindgren (1957) and was estimated from the number of months of the year during which the mean monthly grain temperature was 20°C or above. The minimum breeding temperatures in the laboratory of Sitophilus oryzae (L), Rhizopertha dominica (F), Cryptolestes ferrugineus Steph., Tribolium castaneum (Herbst), Oryzaephilus surinamensis (L), for example, all fall within the range of 15°C to 22°C, and a monthly mean grain temperature of 20°C was considered necessary to allow the insects to multiply sufficiently to become a problem. In looking at the potential distribution of mites, a mean monthly base temperature of 10°C was adopted, and account of rh was taken in some studies. (The rate of increase at various combinations of temperature and humidity are not known outside of the laboratory for most stored-product species, but Howe (1965) summarizes the rate of increase for several insects under laboratory.)

This kind of application of climate data can obviously find a use in the planning of prevention and control measures. Field surveys and advisory (extension) work can be concentrated on areas most vulnerable to infestation. Quarantine regulations affecting storage insects may perhaps be reconsidered in areas where there is apparently little chance of the insects becoming established. On the other hand, we can identify regions likely to require strict enforcement and persistent efforts to eradicate or keep the pests in check.
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ILLUSTRATIONS

Figures 1 to 20
Figure 1 - Relationship of storage temperature and grain moisture content to insect heating, fall in germination (to 95% in 35 weeks' storage) and damp grain heating (broken lines indicate extrapolation) (From Burges, H.D. and Burrell, N.J. (1964), J. Sci. Fd. Agric. 15)
Conversion factors:
\[ \text{Mg CO}_2 \times 4.6158 = \text{B.t.u. per 100 lbs. dry matter} \]
\[ \times 0.0004077 = \text{lbs. water produced per 100 lbs. dry matter} \]
\[ \times 0.0006823 = \text{lbs. dry matter lost per 100 lbs. dry matter} \]

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(By courtesy of the Slough Laboratory, Ministry of Agriculture, Fisheries and Food)

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<table>
<thead>
<tr>
<th>Relative Humidity of air at 23°C</th>
<th>Temperature °C</th>
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<tbody>
<tr>
<td>30</td>
<td>13 16 22 28 33 38 42 65 80</td>
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Key: m.mites; f.fungi; i.insects; b.bacteria; g.germination
(Example: seeds germinate at a minimum relative humidity of 95% and between the temperatures 18°C and 42°C)

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