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Preserving Grain Quality by Aeration and In-store Drying

Proceedings of an international seminar held at Kuala Lumpur, Malaysia, 9–11 October 1985

Editors: **B. R. Champ and E. Highley**

Sponsored by:

Group for Assistance on Systems relating to Grain After-harvest (GASGA)

Australian Centre for International Agricultural Research (ACIAR)

National Paddy and Rice Authority, Malaysia (LPN)

Malaysian Agricultural Research and Development Institute (MARDI)

ASEAN Food Handling Bureau (AFHB)

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Address of Welcome

ON BEHALF OF the joint organisers of this seminar, it is my pleasant duty to welcome the Hon. Deputy Minister of Public Enterprises, Y.B. Tuan Haji Daud bin Dato' Haji Taha, distinguished guests and participants to this auspicious occasion. I would like to express our great appreciation to the Hon. Deputy Minister for taking time off his busy schedule this morning to address the assembly and to officially open the seminar.

I am especially delighted to welcome distinguished colleagues from all parts of the world. Besides participants from the ASEAN countries — Indonesia, Philippines, Singapore, Thailand and Malaysia — we also have participants from outside the region namely: Australia, Bangladesh, Burma, Italy, Kenya, Korea, Nepal, Sri Lanka, United Kingdom, the United States of America, and West Germany. To all of you, I bid you 'SELAMAT DATANG' and welcome to Malaysia.

As you may be aware, this seminar is made possible by the joint efforts of several organisations, both local and international. These organisations are the Group for Assistance on Systems relating to Grain After-harvest (GASGA), the Australian Centre for International Agricultural Research (ACIAR), the National Paddy and Rice Authority of Malaysia (LPN), the Malaysian Agricultural Research and Development Institute (MARDI), and the ASEAN Food Handling Bureau (AFHB).

During the last decade, the Malaysian Government has undertaken several measures aimed at increasing our domestic rice production by the intensive use of land, application of better seeds and husbandry techniques, and efficient water management. However, there is now the realisation that such an increase in grain output would not be possible unless adequate steps are taken simultaneously to prevent or minimise the losses and wastage of food and grain during and after harvest. In fact, the problem of postharvest losses in the course of handling, transportation, drying, and storage has been a serious concern to us. This problem is further aggravated by some operational difficulties encountered by the rice industry during peak harvests, such as insufficient labour supply and excessively wet grain brought to the mills by farmers without any pre-cleaning or pre-drying at farm levels.

The climatic conditions of Southeast Asia are very favourable to rapid insect and microbial growth and in general create unique problems for grains storage. Studies have shown that among the major problems of grain handling, three stand out, namely: grain quality deterioration, dry matter loss, and pest infestation due to rodents, birds and insects. Therefore, I hope that this gathering of experts in grain storage and preservation will contribute significantly to the improvement of grain quality maintenance in the humid tropics of Southeast Asia. I believe that the seminar will provide the necessary framework for the upgrading of grain postharvest technology in our respective countries, with particular emphasis on appropriate storage aeration and in-store drying facilities thereby reducing the losses that we are faced with at present.

I hope that you have a successful seminar, and a pleasant and enjoyable stay in Malaysia.

Shaharuddin Hj. Haron
Director-General
National Paddy and Rice Authority

Research Cooperation in Southeast Asia

I WELCOME the opportunity to participate in the opening session of this seminar.

ACIAR is pleased to join with GASGA, LPN, MARDI, and AFHB in cosponsoring this seminar. Meetings such as this represent a critical element in collaborative agricultural research by bringing together multidisciplinary expertise to consider particular approaches to solving problems. In this case, physical, biological, and social scientists from around the world have been assembled to review the principles, economics, and applicability of the aeration and in-store drying strategies available.

As well as reviewing the state of the art of research and technological development in the field, international meetings can provide important guidance for research planners by identifying gaps in existing programs, and by generating proposals for additional research and development initiatives. Thus, this type of forum is particularly valuable to organisations such as ACIAR in determining priorities for investment in collaborative agricultural research.

ACIAR was established by the Australian Government in mid-1982 to encourage and support research into the agricultural problems of developing countries in fields in which Australia has a comparative advantage. The agricultural research community in Australia has considerable capacity to contribute to the resolution of food production and postharvest problems in the Southeast Asian region. Moreover, Australia's overseas aid policy focuses primarily on its near neighbours in Southeast Asia (especially the ASEAN countries), Papua New Guinea, and the South Pacific.

Against this background it is worth noting the extent of ACIAR's commitment to collaborative agricultural research in Southeast Asia. By late 1985 ACIAR had approved 72 research projects with a value of approximately $A33 million. Joint projects involving Australian scientists and partner scientists in this region account for 54% of ACIAR's current project commitments. ACIAR's Policy Advisory Council, which includes three representatives from the region, has recommended that up to 60% of the Centre's resources should be dedicated to the Southeast Asian region in the longer term.

Of ACIAR's 11 program areas, postharvest research and technology is the largest in terms of research expenditures. Just over 23% of the total value of ACIAR's financial commitment to research programs is allocated to postharvest activities, almost all of which are centred in Southeast Asia.

The relatively high initial investment by ACIAR in research on the safe storage of grain in the tropics mainly reflects the priority given to this area of research by the ASEAN countries. The economic importance of postharvest losses and quality deterioration suggests that even a small reduction in the percentage of losses would yield high rewards.

The dimension, complexity, and impact of postharvest loss problems highlight the need for scientists to work in partnership in strategically planned, cooperative research programs. The highly cooperative and interactive mode of operation adopted by the ASEAN crops postharvest and food-handling programs is an outstanding example of effective collaborative research being undertaken on a regional basis. ACIAR's projects in this field fit comfortably into this framework and benefit enormously from the well-established cooperative links already in place.

This seminar is itself indicative of the close research cooperation in the postharvest area. As mentioned previously, five agencies are directly involved in the organisation and sponsorship of this meeting, while many others have contributed indirectly or through representation. The recent seminar on 'Pesticides and Humid Tropical Grain Storage Systems' held in the Philippines last May, and which attracted some 200 participants, was similarly sponsored and organised by a number of agencies.

The importance of regional research cooperation cannot be over-emphasised both from efficiency and developmental perspectives. There is considerable common ground in terms of production and postharvest problems being experienced throughout Southeast Asia. With many national and international agencies willing to contribute to resolutions, careful planning and close collaboration are desirable if the rates of return on investment of scarce research resources are to be optimised.

One of the criteria applied by ACIAR in evaluating research proposals concerns an assessment of potential spillover effects of research results to countries or regions other than the one where the research is to be undertaken. This is a useful indicator of the broader applicability of research results, and can significantly enhance the potential benefits to be derived from a project. Clearly, the more effective the collaborative links between countries and regions, the more likely it is that spillover effects will be maximised.

ACIAR has now been involved in a collaborative research project on the topic of this seminar — preserving grain quality by aeration and in-store drying — for two years. This project is operating in three countries in the region — here in Malaysia, in the Philippines, and in Thailand. Progress reports suggest that drying technology is feasible in the humid tropical area, and that there is considerable interest among the various grain agencies operating in the region. No doubt this seminar will provide an indication of the extent of real interest in aeration and drying technology, as well as an assessment of the justification for this research.

A.W. Blewitt
Secretary
ACIAR

Objectives of the Seminar

It is indeed a great honour for me to be given an opportunity to address such a distinguished group of scientists, technologists, economists, and other specialists.

As had been mentioned by my colleague, the Director General of LPN, it is the Malaysian Government's policy and intention to increase the level of domestic rice production and at the same time to increase the income of our paddy farmers. To achieve these we are at the moment concentrating on both the small farm production as well as promoting larger scale commercial estate type of paddy production, learning perhaps from our successes on large-scale production in rubber, oil palm, and cocoa. Such a goal may be realised through sustained, well-defined efforts by all concerned with the industry. One such effort is in the area of research and development (R & D). I am glad to inform the gathering that extensive R & D efforts and linkages are already in existence in Malaysia; between the local agencies such as MARDI, LPN, UPM and other universities and agencies; between Malaysia and her ASEAN neighbours, particularly under the ASEAN-Australia and ASEAN-EEC programs; between Malaysia and other government and international agencies such as ACIAR, IDRC, FAO, and UNDP programs. Such linkages have provided an opportunity for us in increasing the skill and depth of multidisciplinary, multi-prong approaches to solving the problems faced by the rice industry.

The Malaysian National Agricultural Policy has given top priority to rice production, being the staple food of the country. In line with that we have established a wide R & D coverage ranging from agricultural production activities to grain primary processing to storage and marketing. The range of disciplines covered include rice breeding, agronomy, pest management, mechanisation, water management, socioeconomic studies, postharvest grain handling, drying, storage of paddy, milling, storage of milled rice, distribution and marketing.

The varying disciplines no doubt need to be coordinated and tuned to the general as well as specific needs of the industry. Within MARDI itself we have established a special research division, the Paddy Research Division to look into the overall needs of the industry. The specific and specialised needs are being contributed by the various R & D support divisions within MARDI such as the Central Analytical Division for the basic studies on soils, agricultural engineering, water management, seed technology, biotechnology and other basic sciences support; the Techno-economic and Social Studies Division for socioeconomic support and the Food Technology Division for the postharvest and processing components. At the inter-agency and industrial level, we have management committees to scrutinise our R & D plans and strategies. At another level, we have committees to help in the implementation of the R & D activities.

All these setup and coordination efforts are necessary because, as all of us know, R & D is an expensive tool of progress and development. Thus, R & D needs to be well planned and managed. The objectives need to be clearly defined and the implementation needs to be effectively managed to ensure that the expected results are obtained not only within the time frame needed by the industry, but also to be of relevance to the dynamic nature of the industry. In other words, any solution created through R & D needs to be appropriate to the peculiarities of the industry.

This seminar I feel is doing just that — reviewing the technology of a specific problem of the industry, i.e. in preserving grain quality through the process of aeration and in-store drying. The seminar will, I understand, review the current state of knowledge on the principles of in-store drying and aeration — in particular the technical aspects, to be followed by an assessment, in both technical and economic terms, of the relevance of these principles to the handling of wet grains under the local humid climatic conditions.

These principles and thus the technology of aeration and in-store drying have considerable relevance to the current status of the Malaysian paddy industry, especially in the preventive and corrective options available in solving the local grain handling and storage problems. In fact these principles have already been utilised to a certain extent by the local paddy and rice industry. It is hoped, however, that the discussions in this seminar, on the principles involved, will further enhance our knowledge and understanding of the mechanisms involved in bringing about and maintaining evenly distributed low moisture and temperature conditions within the bulk of grain, especially under the humid tropical conditions. I wish you a most successful and fruitful seminar.

Mohd Yusof bin Hashim
Director-General
MARDI

Keynote Address

IT IS a great pleasure for me to be here on this auspicious occasion and I am deeply honoured to be asked to address the assembly and to declare open this seminar on preserving grain quality by aeration and in-store drying.

On behalf of the Government of Malaysia, I extend our warmest welcome to all the distinguished guests, learned participants, and interested observers. I understand that this seminar has been organised by several international agencies in collaboration with the local organisations, namely the National Paddy and Rice Authority (LPN) and the Malaysian Agricultural Research and Development Institute (MARDI). The Group for Assistance on Systems relating to Grain After-harvest (GASGA), the Australian Centre for International Agricultural Research (ACIAR), and the ASEAN Food Handling Bureau (AFHB) have collaborated and cooperated very effectively to organise this seminar and to bring together a pool of experts of various disciplines who are distinguished leaders in their respective fields.

The Government of Malaysia attaches great importance to matters concerning rice. This is because rice has always been our staple food. It comprises more than 20% of the food consumed by the entire population and constitutes as much as 35% of the diet of the rural population.

Paddy cultivation is the most important agricultural activity next to rubber in terms of employment and land utilisation. Presently a total of 300 000 farm families are engaged in paddy cultivation involving some 477 500 ha of paddy land, which contribute to the yearly production of about two million tonnes of paddy.

Paddy growers in Malaysia are traditionally among the poorest sectors of the rural economy. However, various programs of poverty eradication had been implemented to contain and reduce the magnitude of poverty. The incidence of poverty among paddy growers declined from 88.1% in 1970 to 55.1% in 1983. This decline in the incidence of poverty was a remarkable and profound achievement because it was attained in a period characterised by unfavourable weather conditions and worldwide inflation which led to increasing consumer prices and rising input costs. However, the incidence of poverty among paddy growers continues to be high and above national average, primarily due to the existence of a large number of uneconomic holdings, exacerbated by low yields in areas outside the major irrigation schemes.

Besides the vast investments towards new irrigation facilities, measures were also instituted to increase the net income of paddy farmers especially through a price support scheme and input subsidies. The purchase price of paddy under the Guaranteed Minimum Price Scheme (GMP) was raised from US$120 per tonne in 1970 to about US$210-225 per tonne in 1979. It was further increased to US$285-300 per tonne since 1980, giving a better return to the farmers.

When we consider the large amount of resources, both human and financial, involved in producing food, it is indefensible that substantial amounts of food are lost during and after harvests for lack of conservation facilities and techniques. As such Malaysia now attaches great importance to the problem of postharvest grain losses. Since reduction of these losses would make available thousands of tonnes of food, better incomes to the paddy growers, and at the same time reduced imports and foreign exchange savings for our country would be realised.

Under the double-cropping schemes, the off-season crop has to be harvested in the wet weather. Therefore, the major problem of harvesting this crop is the drying of paddy. If the wet paddy is not dried soon after harvest, it will deteriorate in quality and cause dry matter losses. As a result, growers obtain a poor price. It was in this context that the LPN undertook a nationwide expansion program for construction of a number of rice mill complexes aimed at providing adequate drying, milling, and storage facilities. The need for sufficient processing and storage facilities became more pressing after the extensive use of combine harvesters for harvesting operations in the major rice growing areas. This is due to the fact that harvesting time will be very much shortened thereby increasing the daily production of wet paddy. This has imposed a further burden on the existing drying facilities, both in the private as well as in the public sector mainly resulting from the fact that narrow harvest peaks cannot be efficiently handled by existing facilities. New methods of handling and preservation of wet paddy have to be devised. We therefore place very great hopes that the seminar of this nature will generate new ideas that can be adopted to solve some of our pressing problems.

The Government of Malaysia has always placed great emphasis on the role of research and development in all industries. In the agricultural sector, beside the institutes of higher learning, several research bodies and agencies have been set up to undertake various research and development works. Presently, the LPN, in collaboration with other agencies, particularly MARDI, has carried out a number of research studies which include paddy aeration for silo storage, gastight storage of milled rice, and the bulk handling of paddy. To-date, some of these research findings have been implemented and incorporated in the existing facilities.

In the area of research and development, I see a great need for closer cooperation and collaboration among the various research bodies, both local and international. This is important in order to avoid possible duplication in our works thereby enabling us to utilise our resources more efficiently. It is therefore vital that the free flow and exchange of information and findings be enhanced among the various research bodies and implementing agencies. In view of the different conditions that exist in each country, the implementation of studies from abroad should be by way of adaptation to suit the local situation rather than wholesale adoption. This is necessary to avoid any possible pitfalls and costly mistakes.

The subject of this seminar is of great relevance to the needs of the paddy and rice industry in Southeast Asia. This seminar will highlight the objectives and principles of aeration and in-store drying. It will also endeavour to discuss the systems, designs, and economics for such practices. Their appropriateness and feasibility will be further illustrated by case studies conducted in various countries. I sincerely hope that the proceedings of this seminar will be compiled and be made available as an authoritative and useful text of reference for researchers and developers of grain aeration and in-store drying technologies.

The holding of this seminar reflects the close rapport and established relations which have long existed among the various organisations of the world. This healthy relationship is held in high esteem by us and it is hoped that this chain of relationships will be extended to more countries and more agencies. Whilst you are here attending this seminar, I hope you will take the opportunity to be closer to us by sparing some of your time to get to know Malaysia and its people. I am sure you will discover many similarities between our countries. You will also notice the differences and will learn to appreciate them. We always say that to know Malaysia is to love Malaysia.

Haji Daud bin Dato' Haji Taha
Deputy Minister of Public Enterprises
Government of Malaysia

Objectives of Aeration and In-store Drying

Grain Quality Considerations in Relation to Aeration and In-store Drying

R.A. Boxall and D.J.B. Calverley*

Abstract

This paper considers the assessment of grain quality in relation to various intrinsic and acquired properties of grain. Intrinsic properties include the shape, size, structure, and colour of the grain, and its bulk density, thermal conductivity, equilibrium moisture content, and flowability. Important acquired properties are the presence of foreign matter, physical and pest damage, and abnormal moisture content. The parameters for deterioration in storage and the role of aeration and in-store drying in maintaining quality are discussed. Attention is drawn to the need to take account of the possibly serious effects on grain quality of the drying technique itself when developing a strategy for grain drying.

THE term 'quality' will have different meanings for the different people concerned with the handling, storage, processing, and utilisation of grain, even though all will be looking for grain of 'good quality'. For example, members of the grain trade will want dry, insect-free, undamaged grain which will store well; millers will want grain which will yield a high percentage of finished product; and consumers will be concerned with appearance, flavour, and cooking properties. Variation in grain quality begins with the variety selected by the producer, and is thereafter influenced by the climatic and soil conditions during the growing season, cultivation practices, weather conditions at harvest, and harvesting techniques. It is accepted that, whatever the condition of grain at harvest, quality cannot in general be improved during storage, handling, and processing; on the contrary, it is easily lost. So what is quality?

Definition of Quality

The dictionary definition of the word 'quality' gives it the same meaning as 'characteristic' or 'property'. In these terms every type of grain can be said to possess many properties which in turn contribute to its overall 'quality'. A consideration of the various properties or qualities either alone or together allows the grain to be graded and valued, and enables the design and development of optimum methods of handling, storing and processing. The qualities can be grouped into two broad categories, namely intrinsic and acquired qualities.

Intrinsic Qualities

Intrinsic qualities are those possessed by the whole, unblemished, ripened grain. They include shape, size, structure, and colour, and are of importance in determining the type description of the grain, whereby it can be identified and checked for purity. The physical characteristics of grain such as bulk density, thermoconductivity, equilibrium moisture content, and flowability, are intrinsic qualities important in relation to the design of grain handling and storage facilities.

Grains are living organisms and accordingly contain, in addition to minerals and water, compounds such as carbohydrates, proteins, oils, and vitamins. The nature, proportions, and distribution of these components within the grain are characteristic for each type or variety of grain and may be said to constitute its intrinsic quality of composition, which is related to the nutritional value of the grain.

Important biological properties of grains include the rate of respiration, which is a function of the storability of grain, and the germination potential, which is of importance when grain is used as seed or for malting. These too are intrinsic qualities, as also is the inherent susceptibility to infestation. All

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grains are vulnerable to insect infestation or infection by microorganisms, but different types or varieties are characterised by differences in their relative susceptibility to such attack. This quality is important to those who control the movement of grain through the postharvest system. Grains which are least resistant need to be moved quickly or given greater protection against infestation or infection.

Acquired Qualities

Acquired qualities are those which are not inherent. They are extrinsic and are thus either additional to the normal complement of intrinsic qualities or are the consequence of certain intrinsic qualities being lost or modified. The importance of the acquired qualities depends upon their nature and the extent of their occurrence, but generally they are detrimental to the overall quality of the grain concerned.

Let us now consider some examples of acquired qualities. During the harvesting and threshing operations within the postharvest system, grain is liable to acquire foreign matter such as weed seeds, straw, chaff, sand, stones, soil, etc., the presence of which can have far-reaching effects on the overall quality and the value of the commodity. Organic foreign matter often provides food for insect pests or a suitable substrate for the growth of microorganisms, which are themselves foreign matter but of an active nature. As insect pests and microorganisms multiply within the grain, by their presence they increase the amount of foreign matter and contamination of the grain. Metabolic heat is generated, the grain mass is reduced, grain breakage occurs, and dust is produced. Contamination and foreign matter are terms which are frequently used interchangeably but it is important to distinguish the two. Generally, foreign matter can be readily removed from grain whereas contaminants cannot. The latter include the soluble excretions of pests and other animals, oils, pesticides, pathogenic microorganisms spread by rodents and insects, and toxins produced by certain moulds.

Physical damage, i.e. breaking, splitting, or cracking of the grain renders it more prone to infestation by insects and microorganisms. Such damage is likely to arise at any stage in the postharvest system but particularly during threshing, drying, and processing. It may have consequences on overall grain quality that become especially evident at the marketing stage.

Pest damage will be acquired by grain if it is susceptible to infestation and not protected from such damage. A range of insect pests cause damage to grain either by chewing at it or by boring in it. Moulds and bacteria will spread into and through grains causing discoloration and lesions which may be the only manifestations of infection if grain is dried before complete destruction can occur. Grain may also become discoloured as a result of heat damage caused, for example, by the development of 'hot spots' in bulk-stored grain.

Correct moisture content is important. If the percentage moisture content of the grain is above or below that which might be expected under ambient climatic conditions, or is outside the limits prescribed by a grain grading standard, the grain may be said to have acquired an abnormal moisture content. Such a moisture content may occur through inadequate or excessive drying. An abnormally high moisture content encourages infestation by both insects and microorganisms and it allows the grain to metabolise more rapidly than is desirable, resulting in unwanted chemical changes, germination, premature aging, or increases in temperature leading to heat damage and perhaps self-destruction of the grain. An abnormally low percentage moisture content usually presents fewer problems. Grain is unlikely to become badly infested by insects when very dry, and the risk of microbiological infection is low or negligible. However, when dried too rapidly or overdried, grains may become very brittle so that they are likely to split, crack, or break easily. This of course is undesirable if a whole grain such as rice is preferred by the consumer and it also presents problems for rice millers. In the milling of grains to flour, overdry grain can also cause problems.

Attitudes to Grain Quality

Before turning to the use of drying to preserve grain quality it is important to consider the attitudes to quality that are held by those directly involved.

The subsistence farmer will attempt to minimise the risk of loss and maintain the quality of his grain to a standard which satisfies his family's needs. An important constraint is the availability of family labour to assist with all postharvest operations. Drying of the relatively small quantities (1-2 t) of grain by natural sun-drying is accomplished by regular personal attention to turning the grain and protecting it from inclement weather. Given the opportunity to increase production and achieve a marketable surplus, the farmer is encouraged to grow high-yielding varieties and to adopt multiple cropping of his land. He is then faced with a new set of problems. His capability to harvest becomes overstretched and when his second crop matures in the wet season he is faced with the difficulty of drying a larger quantity of grain.

The technological solution to this problem is difficult. It requires financial commitment; for a dryer and a source of heat, frequently using fossil fuel. A degree of new management skill is also required for the successful operation of the drying system.

The farmer's simplest solution to this problem is to sell most of the moist grain without delay in order to minimise the risk of loss. The problem is then passed to the grain procurement organisation which is liable to be inundated with grain over a very short period of time. Unless grain is purchased against a rigorously applied quality standard, which specifies a safe, low moisture content, then the procurement organisation must provide strategically placed, adequate grain drying/conditioning facilities. The provision of facilities at primary procurement level may be more realistic but major technical and economic problems can arise. The costs of drying have to be incorporated in the quality grading and price structure. The price paid to producers bringing grain to the procurement centres has to reflect the actual drying costs and the amount of water removed from the grain during the process. Thus, the penalties that a farmer suffers through his inability to dry grain can be high.

As more grain is produced, the grading standards are likely to be raised and so unless the farmer can meet the new requirements his financial rewards for increased production are likely to be reduced.

Grain quality standards become a vital issue in the successful operation of a postharvest system. It is rare to find a system satisfactorily serving all interests, from the producers' financial expectations for his crop through to the consumers' preferences for a cheap, palatable food. The inevitable perturbations which result in seasonal variations of shortage and abundance throw a burden on the procurement and marketing organisations' ability and capacity to satisfy all demands at minimal cost.

Maintaining Grain Quality during Storage

The aim of good storage practice is to maintain conditions in the grain that will preserve those qualities or properties considered important by the end user (in marketing, processing, etc) at an appropriate level. Basically, this means prevention of damage and deterioration caused by insects, mites, and microorganisms and protection from birds and rodents. If birds and rodents can be excluded, the rate of deterioration or the loss of quality during storage will depend upon micro-environmental and climatic conditions and will be at its lowest when grain is dry and cool, since the growth rate of microorganisms depends upon moisture and temperature and that of insects mainly on temperature. The grain will, of course, be subject to the normal process of aging, during which the physical qualities and composition of the grain will change. The rate at which aging takes place will vary with the type and variety of grain concerned and will be influenced by environmental conditions. During prolonged storage, grains are liable to suffer changes in texture, colour, flavour, or nutritive value resulting from the effects of moisture and temperature (even in the absence of insects and microorganisms). The changes which occur may not necessarily render the grain unfit for consumption, but they may make it less palatable or less acceptable to the consumer on aesthetic grounds.

Moisture

The moisture in grain is traditionally considered in terms of the percentage moisture content by weight, usually based upon the wet weight of a sample under test. However, when discussing the preservation of grain quality, it is more meaningful to consider the moisture content of the intergranular environment, or the equilibrium relative humidity (ERH) corresponding to a particular grain moisture content. The susceptibility of stored grain to deterioration is correlated to the ERH and not to the moisture content of the grain.

Microorganisms are unable to multiply when the ERH is below 65% although it is generally accepted that to protect stored grain from mould the maximum ERH should be 70%. Insects and mites, however, are most active in the range

60–80% ERH, although some species survive and multiply at 40–60% ERH and a few, for example the khapra beetle *Trogoderma granarium*, can do so at even lower levels.

Temperature

The effects of temperature on deterioration by insects, mites, and microorganisms are quite straightforward. The temperature range favourable to the growth of microorganisms is wide, extending from below 0°C for cold-hardy species of moulds, to over 60°C for certain heat-resistant bacteria. Most storage insects are unable to complete their life cycle at temperatures outside the range 15–45°C and at temperatures below 17°C, insect activity is generally severely reduced. Thus, cooling of grain to 17°C or lower before or during storage provides an effective means of controlling insect infestation. Under certain circumstances it may be possible to cool grain to temperatures low enough to inhibit the activity of fungi.

Grain cooling can be achieved by aeration using ambient or artificially cooled air. The term aeration is usually taken to mean the forced movement of air at low airflow rates for the purpose of cooling rather than drying, although some drying may occur. In tropical climates, storage temperatures are usually in the range 25–30°C, and although some cooling by aeration may be possible to prevent grain deterioration, it is often necessary to pay more attention to reducing grain moisture content as a means of suppressing biological, particularly microbiological, activity and use other methods to control insect infestation when this occurs.

Drying as an Effective Method of Conditioning Grain for Storage

Cereal grains attain physiological and functional maturity at moisture contents ranging between 35 and 45% depending on the crop. Appropriate moisture levels for storage are between 10 and 14% depending upon not only the crop but also factors such as storage temperature. Consequently, timely harvesting and drying at crop maturity is important for achieving a high quality product.

The objective of drying is to reduce grain respiration by removal of excess moisture. This will prevent the qualitative deterioration which may also arise from the growth of microorganisms and the activities of insects and mites. However, the process of drying may itself adversely affect grain quality unless the drying system is selected and operated with care. Whatever method is used, when grain is dried there is likely to be some change in the characteristics which affect overall quality. Generally speaking, the adverse effects on grain quality will increase with the severity of the drying conditions. Damage to the grain may arise if drying is carried out at too high a temperature or too quickly.

The cheapest method of drying is natural drying using the heat of the sun and the evaporative effect of the wind. Grain may be held in cribs or spread in thin layers on the ground or on trays or mats to dry. Natural drying, whilst generally acceptable for traditional farming needs, does leave the grain open to dust, insect infestation, and attack by birds and other vertebrates which may result in losses in quality and quantity.

In the humid tropics natural drying may be difficult or even impossible, especially in those countries where, as a result of multiple cropping, grains must now be harvested in the wet season. Under these circumstances there is a requirement for what is popularly referred to as artificial drying. This can involve the forced movement of ambient or natural air through the grain or the use of heated air as the drying medium.

Drying with natural air is possible when its relative humidity is lower than the ERH of the grain, and even in humid areas, substantial amounts of water can be removed. Although the amount of water removed is never enough to reduce the grain moisture content to a safe level, a system of drying using first ambient air and then heated air may be desirable in preserving grain quality. We shall return to this later.

Drying procedures with heated air are basically of two types, namely low temperature/high volume and high temperature/low volume. Low temperature drying, i.e. at 5–10°C above ambient, may be applied when the grain is held in temporary or extended storage systems, whereas drying at higher temperatures is generally carried out in systems specifically designed to facilitate exposure of grain to the drying air.

The principal constraint on the acceptable length of time during which drying can be completed is grain deterioration due primarily to mould growth. However, the depth of grain and the volume of air used are also important in preventing the growth of mould. The maximum drying time using low temperature air will depend upon the grain type, its physical condition and its moisture content and temperature, all of which equate to the food supply and conditions for mould growth. Fungal deterioration is a dynamic process, involving a succession of microorganisms and resulting in the breakdown of organic matter. During this process carbon dioxide is released and a measurement of the amount of CO_2 produced has been used by various workers (Saul and Lind 1958; Steele et al. 1969) to determine the amount of dry matter loss due to mould growth. They subsequently calculated an allowable storage loss of less than 1%, which provided an indication of grain of acceptable quality.

When the temperature of the drying air is raised, the capacity to remove moisture is increased and so the grain drying can be completed more rapidly. High temperature drying is therefore useful where large amounts of grains have to be dried in a short time. However, there are limits to both the amount of heat that can be added and the drying speed if a high quality grain is to be maintained. These limits are based upon the degreee of physical or heat damage to the grain which results in stress cracks, brittleness, breakage, discoloration, and loss of viability, and the intended future use for the grain.

Effect of Drying on Grain Quality

When grain is overheated during drying, the quality may be affected in a number of ways. At temperatures above 45°C the embryo of the grain will be destroyed, rendering it useless as seed. Maize for the starch industry should not be dried at temperatures above 60°C or the starch separation process will be damaged, as gluten becomes hardened or toughened and clings to the starch.

Quality changes in wheat which is overheated may be manifested in low grade flour, which is unpalatable or has poor baking properties. If the temperature is high and the RH of the air is low, there is a danger that the moisture will be removed more rapidly than water can diffuse from the inner layers of the grain, and a hardening or casing may be formed. This impervious layer will prevent free diffusion of moisture and will cause grains to become so wrinkled, scorched and discoloured that they are rejected completely because of their appearance.

The brittleness in grain which arises as a result of rapid drying at high temperatures is particularly noticeable as stress cracks or checking in the kernels. Paddy, soybeans, and maize are prone to such internal cracking if dried too rapidly and subsequent handling will cause the kernels to break up. This has serious implications for grain quality when the consumer demands whole grains, as in the case of paddy/rice.

It is interesting to note that much of the qualitative deterioration which is likely to arise during drying can be effectively reduced by measures which also conserve energy, such as the processes of 'dryeration' and combination drying. In dryeration, grain is first dried at a high temperature and this is followed by a tempering period before the grain is finally cooled. Stresses which build up in the grain during high-temperature drying are relieved during tempering before the grain is subjected to the additional stresses caused by rapid cooling and which would otherwise result in cracking or breakage of the grain. Combination drying involves an initial phase of high temperature, high-speed drying, followed by further drying at lower temperatures or using natural air. Both methods extend the period of drying and lead to a reduction in the brittleness that would result in grain breakage. Table 1, summarising the work of Foster (1975), shows the relationship between the method of drying and brittleness of maize. A similar problem is recognised with paddy where late harvesting and uncontrolled drying cause cracks in rice grains that cause milling losses (Bhashyam et al. 1985).

Many of the modifications designed to improve the fuel efficiency of grain dryers are likely to have a positive bearing on grain quality. Drying stresses will be reduced if the vapour pressure difference between the moisture in the grain being dried and in the drying air can be reduced. This depends upon the addition of moisture to the drying air and can be achieved by recirculating the drying air.

Table 1. Effect of drying method on britleness of dried corn.

Drying method	Sound kernels without stress cracks (%)	Breakage (%)
Conventional continuous flow	8.8	11.3
Dryeration	60.6	6.7
Partial heat or combination drying	82.2	3.9
Unheated air	93.3	1.6

Lower airflow rates and greater grain-holding capacity per unit of dryer output tend to reduce drying speed, a major factor in causing grain brittleness and qualitative deterioration.

Preservation of Grain Quality by Aeration

When grain has been dried satisfactorily to a 'safe' moisture content and is kept in a store that is structurally sound, it may still be at risk from the effects of serious increases in the moisture content which may be induced by prevailing climatic conditions. Grain may take up moisture directly from the ambient air in the store, or moisture migration from warmer or to cooler parts of the grain bulk may occur.

Moisture uptake is likely to occur in those regions where humidity is consistently higher as in the humid tropics or during a tropical rainy season, and where grain is stored in bags rather than in bulk. Moisture migration, on the other hand, is more likely to occur in grain bulks, especially in metal silos or bins where the grain is in contact with the walls. Under these conditions, solar heating of the silo walls can result in large temperature differentials, i.e. high temperatures at one side or at the periphery of the structure. These differentials can cause convection currents in the grain accompanied by moisture migration from high to low temperature areas. As the air is cooled, its relative humidity rises and may reach saturation at which point excess water will be deposited on the surface of the cooler grain. Localised increases in moisture content can therefore occur and create conditions favourable for the development of microorganisms and subsequent qualitative deterioration. Aeration can prevent the occurrence of these potentially serious conditions and maintain the quality of the stored grain. The passage of air through the grain will have not only a cooling effect but will maintain a uniform, low temperature throughout the bulk.

Developing a Strategy for Grain Drying

Much attention has been devoted to increasing production of cereal crops through the use of improved, high-yielding varieties, double or multiple cropping, and improved production technology and this has inevitably led to a number of problems in the handling of grain after harvest. Farmers now have to cope not only with increased yields but also with crops which mature and have to be harvested during the wet season. Various organisations have responded to the problems by looking at the possibilities of developing improved harvesting or threshing techniques and by introducing grain dryers to replace traditional sun drying. In the humid tropics most agriculture is small-scale and the intended beneficiaries, i.e. the small-scale farmers, find the new techniques, especially grain dryers, too expensive. They therefore have to resort to the traditional method of sun drying. However, suitable drying floors are usually inadequate and periods of sunshine too short to cope with the quantities of grain involved, and so they have no option but to sell their wet paddy early or suffer considerable grain deterioration due to mould damage, germination, and fermentation. A possible solution is to provide a centralised drying system, for example at mills, but experience has shown that these facilities may be inadequate to cope with quantities of grain involved and that millers are sometimes reluctant to invest in grain dryers because of high fuel costs. As a consequence, a severe strain may be placed on the capability of the central grain-handling agencies to dry and store the grain satisfactorily.

When the existing drying facilities cannot cope with the volume of incoming wet grain, alternative methods of handling are required. De Castro et al. (1980) investigated the use of a relatively inexpensive aeration system for paddy in bags, and showed that the rate of quality deterioration, measured by the proportion of damaged and discoloured grains, could be reduced by aeration. Thus, the holding period before drying could be extended but the need to dry could not be eliminated entirely.

There is an increasing interest among central grain-handling agencies, particularly in Southeast Asia, to move from storage of grain in bags to bulk-handling and storage. Associated with this change is the need to introduce a system of in-store drying and aeration to ensure that grain quality is maintained. Methods developed for in-store drying elsewhere in the world, particularly in temperate regions, have proven successful, being cost-efficient and resulting in commercial gains in terms of high quality grain.

The principles and requirements of aeration and in-store drying to prevent grain quality deterioration are well known in the context of temperate conditions. However, aeration and drying requirements will be quite different under humid, tropical conditions and may vary considerably from place to place. For example, it has been reported that tropical aeration requirements are four times greater than the values for temperate requirements and that local conditions on the east coast of peninsular Malaysia at Khota Bharu indicate a need for an airflow rate 50% higher than that needed on the west coast at Alor Setar (Teter 1981). Also, the requirements of drying will be greater than in the temperate regions. Overall, one can expect that energy requirements for aeration and in-store drying in the humid tropics will be greater than in temperate regions and so some care must be exercised when attempting to transfer temperate region technologies to the humid tropics.

Clearly, systems must be cost effective and so there will be a need to consider energy requirements and the effects of various drying parameters in relation to the quality of grain in order to develop an appropriate aeration or drying strategy. Various aspects of grain quality have been discussed, but in developing an appropriate strategy for the humid tropics one must guard against demanding too high a standard for overall grain quality. Ultimately, consideration must be given to providing a good wholesome product, free from contamination, which is acceptable to the local consumers. Industrialised countries' conventional standards of an acceptable commodity do not necessarily apply.

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In-store Drying of Grain: the State of the Art

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Abstract

The objectives of in-store drying are reviewed. Among the topics discussed are: decreasing the moisture content to safe levels; cooling the dried grain to ambient conditions; and cleaning the crop before drying. Alternative in-store drying techniques are compared with high-temperature automatic batch drying. Included in the comparison are natural air drying, low-heat drying, solar drying, in-store counterflow drying, 'dryeration', and combination drying. The use of grain stirrers and biomass energy with in-store drying installations is assessed.

The main criteria to be considered in evaluating the various methods of drying are grain quality, energy efficiency, capacity, operating costs, and farmer expertise. All in-store drying methods result in improved grain quality compared with high-temperature drying. Natural air drying produces the best quality (if properly operated), and needs the least amount of energy. However, its capacity is low and it requires the most attention and expertise of the farmer. Solar in-store drying is technologically attractive, but is of questionable economic value, at least in the United States. Grain stirrers are of value in low-heat systems in preventing the occurrence of a large moisture gradient in the bin.

Furnaces fired on biomass can supply the energy required for grain drying. The concentric vortex-cell biomass furnace, integrated into an on-farm, in-store counterflow grain dryer, is evaluated for potential use in the tropics.

THE prime objective of grain drying is to decrease the moisture content of recently harvested grain from 22–30% (wet basis, w.b.) to 12–14% (w.b.) in order for the crop not to deteriorate in quality during the subsequent storage period (Brooker et al. 1974). It depends on the end-use of the grain which quality characteristic needs to be conserved; for rice, head yield and cooking quality are essential, while for wheat the baking quality needs to be maintained. If the grain is to be used for seed, the viability has to remain high.

Grain is dried in various ways (Bakker-Arkema et al. 1978). Traditional sun drying, in which the wet grain is spread out on the ground in the open air, is still practiced in many parts of the world; the resulting grain quality is marginal at best, and the system is weather dependent. Much of the grain in the tropics is still handled and dried in bags, but the transition from bag to bulk handling and drying appears only a matter of time. Therefore, only bulk drying is considered here.

In-store drying of bulk grain requires a structure to hold the grain (e.g. a bin) along with a mechanical air-movement device (e.g. a fan), and usually an air-heater; natural air drying, low-temperature drying (also called supplemental-heat drying), ammonia drying, combination drying, batch-in-bin drying, and in-bin counterflow drying are in-store drying systems; each is able to produce excellent quality grain when properly designed and operated (Bakker-Arkema 1984). High-temperature continuous-flow dryers are found at high capacity installations such as rice mills and grain terminals; often the grain quality is deleteriously affected by the high air-temperature and drying rates (McLean 1980). Only in-store drying systems will be considered in this paper.

The initial cost, the grain quality, the energy efficiency, the operating costs, the weather patterns, and the farmer expertise required are among the major criteria for selection of in-store drying systems. Since no drying system ranks first in every category, the best choice of a dryer for a particular location will be a compromise. This is true for the humid tropics as well as for other regions where grain is dried.

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In-store Drying Systems

In-store grain drying systems can be classified into: (1) high initial moisture content/high air-temperature systems, and (2) intermediate moisture content/low air-temperature systems. The dividing line in moisture content is about 21–22% (w.b.), and in air-temperature 30–40°C. A comparison of continuous-flow and in-store drying systems for paddy has been made by Bakker-Arkema et al. (1983).

High Moisture Content/High Temperature Systems

Batch-drying, combination drying, and in-store counterflow drying are methods for drying bulk grain regardless of the initial moisture content. The temperature of the drying air in these systems ranges between 45° and 75°C, the airflow rate between 10 and 30 m³/minute/t. The success and capacity of the systems is not dependent on the weather conditions.

Batch drying (also called batch-in-bin drying to distinguish it from mobile, high-temperature batch dryers) is limited to the drying of relatively shallow layers of grain (1–1.5 m) in order to prevent serious overdrying of part of the grain. Drying and cooling of the moist grain takes place in 4–8 hours depending on the initial moisture content, the air temperature and the airflow rate (Brooker et al. 1974). Batch drying to safe-storage moisture contents (11–14%) is not weather dependent, requires little operator expertise, causes overdrying of some grain with a resulting quality deterioration, and is not energy efficient (Kalchik et al. 1981). Unless high capacities are required, in-store batch drying in the humid tropics should be limited to combination drying systems.

Combination drying or two-stage drying is a process in which high-capacity, high-temperature, high-airflow drying to an intermediate moisture content of 17.5–22% is followed by in-store low-temperature, low-airflow drying and cooling to 12–15% (w.b.) (Morey et al. 1981). The high-temperature, high-airflow phase of combination drying can be an in-store batch system (as discussed in the previous paragraph) or a mobile batch dryer. The low-temperature, low-airflow phase of combination drying can be accomplished by ambient air or by slightly heated air (i.e. natural air drying or supplemental-heat drying), and may require from two days to two months depending on the initial moisture content of the grain placed in the bin and on the temperature and airflow rate of the drying air (Morey et al. 1981). *Dryeration* is the best known combination drying system; the intermediate moisture content is 17–18% (w.b.), ambient air is used at a rate of 0.5–1.0 m³/minute/t for final drying and cooling after a 6–8 hour tempering period in a special tempering bin (McKenzie et al. 1972). Several combination drying systems are compared in the next section.

In-store counterflow drying is a combination drying system and consists of two bins, one of which is a heated-air counterflow dryer (Bridges et al. 1981). Wet grain, regardless of moisture content, is loaded into the first bin and dried until the bottom 8–12 cm layer has reached a moisture content of 16.5–19.0% (w.b.). The partially dried, hot grain is removed from the bottom of the store by a tapered sweep auger, and is transported to a second bin where final drying and cooling take place. The air temperature in the first bin is 40–45°C for rice and 70–95°C for maize; the airflow rate is 10–30 m³/minute/t, depending on the depth of grain in the bin. Ambient air is used in the second bin; the airflow rate is a low 0.5–1.0 m³/minute/t. Removal of the partially dried grain from the first to the second bin is intermittent; the time between cycles of the unloading auger depends on the airflow rate, the initial grain moisture content, and the drying air temperature, and varies from 15 to 150 minutes. If the logistics allow, final drying and cooling in the second bin should be after a 4–8 hour tempering period in order to optimise the energy efficiency and grain quality of the system. In-bin counterflow drying is a very flexible in-store drying system and is being used extensively in the United States both for maize and paddy (Bakker-Arkema et al. 1980); only the relatively high initial cost might interfere with widespread adoption of the system in the humid tropics.

Intermediate Moisture Content/Low Temperature Systems

Natural (ambient) air drying, supplemental-heat drying (also called low-temperature drying), and trickle-ammonia drying are limited to the drying of grains with an initial moisture content below 21–22% (w.b.). The drying air temperature in these systems ranges from ambient to 1–5°C above ambient; the airflow rate is between 0.5–4.5 m³/minute/t. The systems are dependent on the weather conditions. Some newly designed units are under microprocessor control (Mittal and Otten 1983).

Natural-air drying and *supplemental-heat drying* systems are similar; the grain is dried and cooled in the bin in which it is stored. The distinction between the systems is that no heat (except fan energy) is added to the drying air in natural-air drying, while the drying air-temperature is increased 3–5°C in supplemental-heat systems in order to decrease the relative humidity of the ambient air to below 55%. The success of a natural air drying system depends to a large extent on the moisture conditions of the ambient air at the time of drying. If the relative humidity during the wet season is consistently over 75% grain cannot be dried properly with ambient air and the use of supplemental-heat becomes mandatory (Mühlbauer et al. 1981). The minimum required airflow rate depends on the grain moisture content and on the locally expected weather conditions. This is illustrated in Table 1, in which the minimum airflows for natural-air, low-temperature (supplemental-heat), and solar drying systems are tabulated for 12 North-Central states in the United States (Pierce and Thompson 1979). Note the much higher airflow requirements for a warm, humid climate (i.e. Indianapolis) than for a cool, dry climate (i.e. Bismarck). In evaluating the data in Table 1, it should be kept in mind that the required airflows are based on 10-year weather data, and a failure of one out of ten years. Although the natural-air and supplemental-heat in-store drying systems require considerable operator expertise and are low-capacity units, both are able to produce excellent quality grain at low operating costs and energy requirements. In order for natural-air and supplemental-heat drying to be successful in the humid tropics, the minimum airflow rates along with the maximum initial grain moistures should be determined for the different provinces in each of the grain-producing countries of the humid tropics. Good weather records are therefore required.

Table 1. Minimum airflow requirements (m^3/minute/t) for one location in each of the north central region states in the USA, assuming an initial moisture content of 24% (w.b.) and a harvest date of 15 October. These values are based upon simulated drying results for a 10-year period. Increase these values by 50% for design purposes.

Location	Natural air[a] Next to worst	Solar drying[b] Next to worst	Low-temperature[c] Next to worst
Chicago, IL	3.01	2.41	2.49
Indianapolis, IN	4.57	2.37	2.09
Des Moines, IA	2.43	2.51	2.19
Dodge City, KS	2.48	2.36	2.36
Lansing, MI	3.07	2.56	2.61
St Cloud, MN	2.13	1.96	1.94
Columbia, MO	2.77	3.10	2.44
Lincoln, NE	2.31	2.23	2.00
Bismarck, ND	0.64	0.60	0.60
Mansfield, OH	2.84	2.12	2.06
Huron, SD	1.56	1.35	1.26
Madison, WI	2.50	2.09	1.97

[a] A 1.1°C temperature rise due to drawing the air over the fan motor was assumed.
[b] Heat supplementation includes the 1.1°C from the fan plus a solar collector capable of providing a 24 hour average temperature rise of 1.7°C when collecting 1255 J/cm²-day.
[c] 2.8°C temperature rise from electrical heater and from the fan.
Source: Pierce and Thompson (1979).

Trickle-ammonia drying is a technique recently developed in the United States for in-store drying of maize, mainly for animal feed (Nofsinger et al. 1979). High moisture content grain (up to 26–28% w.b) is slowly dried over a 1-5 months period with ambient air at low airflow rates (1–2 m^3/minute/t) with a low level of anhydrous ammonia being injected into the airstream intermittently. The ammonia is applied initially at a 0.05% level. To suppress microbial activity permanently, weekly injections of NH_3 are required until the grain has reached the safe storage moisture content (Hsieh et al. 1979). Other chemicals used for this process are formaldehyde, methylene-bis-propionate, and sulphur dioxide (van Cauwenberge et al. 1983). The trickle-ammonia process is energy efficient, minimises mould development, and operates over a wide range of weather conditions; at least in the United States it is also cost effective. The potential of trickle ammonia grain drying in the humid tropics should be evaluated.

In-store solar drying of grains has been the topic of extensive recent research (Anon. 1980; Kranzler et al. 1980; Fraser and Muir 1981). The solar energy available at a particular location depends on the latitude, the time of year, the weather conditions, and the solar collector design. Although solar grain drying has been proven technically feasible, there is a wide diversity in opinion on the economic feasibility (Morey et al. 1979; Peterson and Morrison 1984). Only in those areas of the humid tropics where the price of the solar collector construction materials and the labour costs are low, and the fossil fuel costs are high, should in-store solar drying of grains be considered. Simulation has been used extensively to find the optimum airflow rates for in-store solar drying installations in various locations (Hasnaoui 1983).

Table 2. Standardised energy consumption for five alternative combination drying methods in Michigan, USA (43°N latitude).

Drying technique	Electricity[a] (kWh/ha)	Propane (L/ha)	Energy efficiency (kJ/kg)	Total energy[b] propane equiv. (L/ha)
Natural Air[c] (26-23-15.5% m.c.)	343.0	72.9	3227	121.6
Low-temperature[c] (26-23-15.5% m.c.)	481.9	79.9	3756	141.1
In-bin dryeration[c] (26-20-15.5% m.c.)	94.4	142.1	4140	155.2
In-bin counterflow (26-18-15.5% m.c.)	103.5	156.2	4548	171.0
Automatic batch (26-15.5% m.c.)	33.4	287.9	6589	292.6

[a] Based on 62.5 t, initial moisture content (m.c.) 26.0% (w.b.), final m.c. 15.5%
[b] Based on 6.9 t/ha.
[c] Energy efficiency of high-temperature drying phase is 6228 kJ/kg H_2O.
Source: Kalchik et al. (1981).

A three-year experimental investigation of five on-farm maize drying systems has been conducted recently in the temperate climate of the northern U.S. state of Michigan (Kalchik et al. 1981). The energy requirement of the five in-store drying systems for drying maize from 26% (w.b.) to 15.5% (w.b.) is shown in Table 2. The high-temperature batch system required more than twice as much energy (292.6 litres of propane per ha) than the combination drying system of batch/natural-air (121.6 L/ha; the other three combination drying systems (e.g. batch with low-temperature, dryeration, or counterflow) fall somewhere between these energy consumption values. In terms of grain quality, Table 3 shows that ammonia drying, natural air drying, and low-temperature drying produced good quality maize. Note that in-bin counterflow drying produced considerably less stress cracking than batch drying.

It is dangerous to transfer the in-store drying results of Tables 1 and 2 directly to the humid tropics. Although there is no question that each of the systems can be successfully operated under more humid and warmer conditions, the airflow rates have to be adjusted to the local weather conditions and should also account for dry or wet season operation.

Table 3. Maize quality parameters for five alternative in-store comibnation drying methods, compared with batch drying.

Drying technique	Moisture content: Initial %, w.b.	Intermediate %, w.b.	Final %, w.b	Stress cracks %	Breakage tests %	BCFM %	Viability changes %
Natural air	26.2	23.1	14.4	2.8	11.9	0.0	43.4
Low-temperature	27.5	23.0	13.8	3.4	13.1	0.0	41.8
In-bin dryeration	24.0	20.0	15.6	9.0	13.8	0.0	63.7
In-bin counterflow	26.4	18.3	16.3	64.0	29.0	0.2	28.5
Batch	26.0	—	15.5	87.3	46.3	0.5	78.0
Ammonia drying	25.6	—	15.6	0	9.4	0.0	65.0

Source: Kalchik et al. (1981).

Auxiliary Equipment

Pre-cleaners

Pre-cleaning of the grain before in-store drying is recommended if economic use can be made of the separated material. The small pieces of broken kernels and foreign material deteriorate more rapidly than whole kernels after in-store drying of the grain. In addition, the airflow through the grain in a bin is restricted by the small particles, or fines; the effect of the fines on the static pressure in maize has been quantified by Grama and Berne (1982).

The pre-cleaning is usually accomplished with rotating cylindrical screen machines or vibrating screen devices. Brook and Foster (1981) listed the recommended screens for the different grains.

Grain Stirrers

Overdrying of the bottom layers and non-uniform drying of the grain mass are common faults of in-store drying systems. Grain stirrers are designed to overcome these problems, and are in common use in the United States (Bern et al. 1982). A grain stirring system typically consists of one or more 51-mm augers suspended from the store roof and sidewall, and extending to near the perforated bin floor. The augers lift the grain near the bin floor towards the top of the bin surface while moving in a predetermined pattern through the bin at a horizontal travel rate of 2 to 10 mm/s.

Stirring devices have been used successfully for both high and low-temperature in-store drying systems (Colliver et al. 1979). Their use in the subtropics might not be justified because of the high initial cost. Even in the United States stirring is economical for in-store supplemental-heat drying only for certain bin diameters and commodity price levels (Loewer 1983).

Biomass Furnaces

Biomass in the form of rice hulls, straw, maize cobs, or woodchips appears to have promise as a replacement for petroleum-based fuels in in-store grain drying (Montalembert 1983). The economics of biomass utilisation depends on the relative cost of the available biomass fuels compared with fossil fuels. Table 4 illustrates this point for the United Kingdom in 1982 (Blakeman 1982).

Table 4. Fuel costs in the United Kingdom in 1982.

Fuel	Gross cost[a]	Gross calorific value	Overall efficiency (direct-fired)(%)	Cost/ useful MJ
Electricity	3.55 p/kWh	3.6 MJ/ kWh	100	0.98 p
Natural gas	27.2 p/therm	105.5 MJ/ therm	98	0.26 p
Bulk propane	13.4 p/therm	26 MJ/L	98	0.53 p
Bottle propane	£8.65/kg	50 MJ/kg	98	0.93 p
Diesel oil	17.p/L	40 MJ/L	95	0.45 p
Coal	£60/t	25600 MJ/t	75 (indirect)	0.31 p
Straw	£20/t	16800 MJ/t	65	0.18 p
Wood	£30/t	19800 MJ/t	70	0.22 p

Source: Blakeman (1982)

[a] £1 = 100 p = US$1.40

Michigan research is at present centred on the improvement of the combustion efficiency of biomass furnaces, on the reduction of emissions, and on the automation of the furnace controls (Mwaura et al. 1983). Two major types of combustion furnaces are found: direct combustion (Claar et al. 1981) and gasification-combustion (Richey and Foster 1980). In a direct-combustion furnace, the energy from the burned biomass is transmitted directly to an airstream which is mixed with ambient air to give the required drying air temperature; concentric-vortex direct-combustion furnaces have proven to be the most efficient (Anderson et al. 1981). In a gasification-combustion furnace, producer gas which can subsequently be burned in a conventional gas heater is generated. Barrett et al. (1981) compared the two furnace types and concluded that there are no significant differences between them in terms of heat recovery and particulate emission. Maize dried with direct-combustion energy does not contain harmful deposits (Jacko et al. 1981; Mwaura 1983).

The technical feasibility of the biomass furnace for in-store drying has been proven. The main drawback of widespread adoption is the high capital cost. Mwaura (1983) showed that the fossil fuel costs in the United States have to rise substantially over the next decade for biomass installations to become economically viable for in-store grain drying. It appears that economic viability for the biomass furnace is closer to reality in some of the countries in the humid tropics (e.g. Brazil).

Conclusions

Two-stage drying, also called combination drying, is recommended for the drying of rough rice and maize with moisture contents over 20-21% (w.b.) in the humid tropics. Relatively high drying temperatures are required in the first stage; ambient air is usually sufficient for the drying process in the second stage. During wet weather, supplemented heat drying should be considered in the second stage drying. The required airflow rates in combination drying systems should be tailored to the local weather conditions.

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Some Fundamental Principles and Benefits of Aeration of Stored Grain

G.R. Thorpe*

Abstract

Aeration is the process of blowing air through stored grain with the principal objective of cooling the grain. It differs from in-store drying in so far as the airflow rate used in aeration is an order of magnitude lower than that used for drying, and it is therefore not an energy intensive process. This paper outlines and quantifies the advantages of aeration, which include reducing insect population growth rates, lowering the rate of pesticide decay, preserving grain quality, and lessening the incidence of moisture migration. The paper also describes, with examples, the fundamental processes of heat and mass transfer that govern the rate and amount of cooling during the aeration process.

A powerful statistical tool for estimating the climatic conditions that are likely to occur during aeration is described, and the use of the method is illustrated by means of an example that draws upon temperature data published in daily newspapers. Climatic conditions that prevail in tropical regions may not be suitable for significant benefits to accrue from aeration, and it may be necessary to lower the total heat content of ambient air before it is introduced into the grain. Two methods of modifying the air state, namely the use of a suitably modified commercial air conditioner or the isothermal drying of air in a solar cooling device, are described. It is shown for example, that the solar cooling device is capable of cooling grain to less than 18°C, as opposed to 25°C in a typical tropical environment.

FOOD grains are harvested seasonally, but consumed continuously. Hence, they have to be stored for several months. If it is planned to build up a strategic stock of food grains to act as a buffer against years of poor harvest, then they may have to be stored in good condition for many years. During storage, losses may be severe because of attack by insects, mites, moulds, rodents, and so on. For example, grain losses in Southeast Asia are reported in Champ and Highley (1981) to be in the range 5–15%. In India, Krishnamurthy (1975) reports postharvest losses as being 9%, although they sometimes exceed 50% (Khare, 1975). The single largest component of losses results from insect infestation. Insect infestations also pose a threat to grain-exporting countries, which are contractually bound to present their grains to international markets free from live insect pests.

Two key variables that affect the storability of grains are their temperature and moisture content. As a general rule, reducing either or both of these variables results in an enhanced grain storage environment. Forcing air of the appropriate thermodynamic state through a grain mass can result in the grain being either cooled or dried (or a combination of the two). If stored grain is to be dried within a month or so the airflow rate must be quite high, i.e. about 20 litres per second per tonne. Even if the air temperature is not modified by heating it, in-store drying is still energy intensive because of the power required to force air through the grain. The airflow rate required to cool grain is, however, considerably less, about 1 L/sec/t and this is a process consuming small amounts of energy. If ambient air is used, the cooling process is referred to as ambient air aeration, or sometimes natural aeration. In some geographical locations, ambient air may have too high a heat content, or enthalpy, to effect sufficient cooling, in which case it must be cooled or dehumidified before being used for aeration. Aeration is generally applied when the heat content of the air expelled from the grain bulk exceeds that of the air entering the grain.

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Benefits of Aeration and Grain Cooling

Cooling grain by either ambient aeration or, where necessary, refrigerated aeration is a very powerful method of protecting stored grains. Some of the benefits pointed out by Esmay, Trott, and Thorpe[1] are:

(a) It reduces, or may even completely suppress the growth of insect pest populations.
(b) The amount of pesticide required to give long-term protection from insect pests may be significantly reduced. Furthermore, if either ambient or refrigerated aeration is used to cool the grain, the rate of decay of pesticide becomes independent of the initial grain state.
(c) Grain quality is preserved, which is particularly important when storing grains for seed or for further processing.
(d) Aeration may be used for short-term preservation of damp grains while awaiting the availability of drying facilities.
(e) Grain cooling by aeration reduces temperature gradients in stored grains, and this reduces the incidence of harmful moisture migration.
(f) Aeration consumes little energy and relies on simple technology.
(g) Grain cooling is safe, does not require rigorous storage sealing standards, and it fits easily into existing grain handling strategies.
(h) By reducing population pressure, grain cooling may be expected to slow the rate at which insects become resistant to chemical pesticides.

Some of the above benefits will be quantified in this paper.

Components of an Aeration System

Aeration systems consist of a fan, a supply duct leading from the fan to a perforated duct placed in the store, and provision for airflows into or out of the air space over the grain surface. There may also be a return duct if recirculatory fumigation is to be carried out. The components of an aeration system for bulk grain are shown in Figure 1, and the components proposed for a system to treat bagged grain in Figure 2. Hunter these proceedings describe how fans and aeration ducts are specified for a given cooling duty.

[1] M.L. Esmay, A.R. Trott, and G.R. Thorpe, Modified environment in agricultural buildings for developing countries: to be published by FAO, Rome.

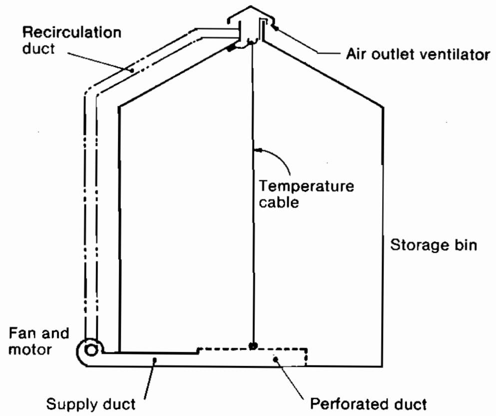

Fig. 1. Principal components of an aeration system for bulk grain.

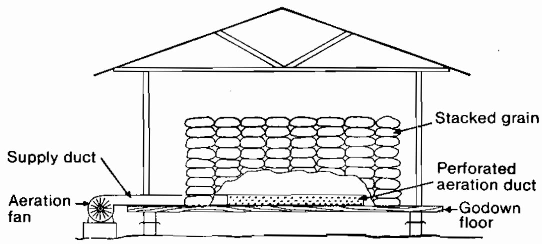

Fig. 2. Principal components of an aeration system for bagged grains.

Principles of Aeration

Cereal grains are hygroscopic materials; that is, they absorb and desorb water such that their moisture contents are a function of the relative humidity and temperature of the air surrounding them. Hence, when damp grains are aerated with ambient air they may dry as well as cool. The drying of the grains has a very profound effect on the degree of grain cooling, because as the air enters the grain, latent heat of vaporisation is required to effect grain drying. Hence, it is possible for a bed of wet grain to cool to a temperature that is lower than that of the ambient air used for aeration. At normal aeration rates (1 L/sec/t), under an aeration schedule of 3 hours per day, it may take up to 10 years for the grain to be dried and cooled such that it is in thermodynamic equilibrium with the ambient air. In order to design aeration systems it is essential that these phenomena be quantified, and to do this we must consider some basic principles.

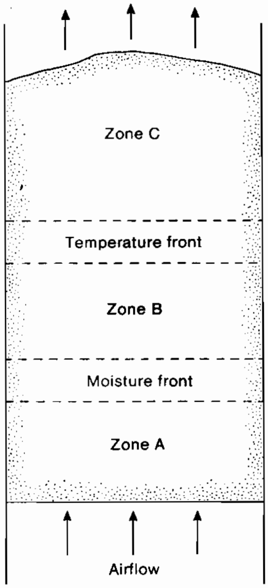

Fig. 3. The formation of temperature and moisture fronts in an aerated or dried bulk of grain.

Fronts and Zones

It has been pointed out[1] that when air is forced through a bulk of grain, three zones are formed (A, B, and C, say), and each zone is separated by a front or change zone as shown in Figure 3. These fronts move through the grain as waves, identically in the direction of the airflow. The most rapidly moving point on a wave is called the leading edge, whilst the slowest moving point is called the trailing edge.

The grain in zone A is in moisture and temperature equilibrium with the inlet air. Its moisture content can therefore be found by reference to a pychrometric chart, such as the one shown in Figure 4. When designing drying systems, as opposed to aeration systems, the objective is usually to ensure that zone A occupies the entire bed of grain. The grain in zone C has not been affected by the cooling process and is at its original moisture content and temperature.

When designing aeration systems the airflow rate and aeration schedule are chosen so that the bed is occupied by grain mostly in zone B. But how

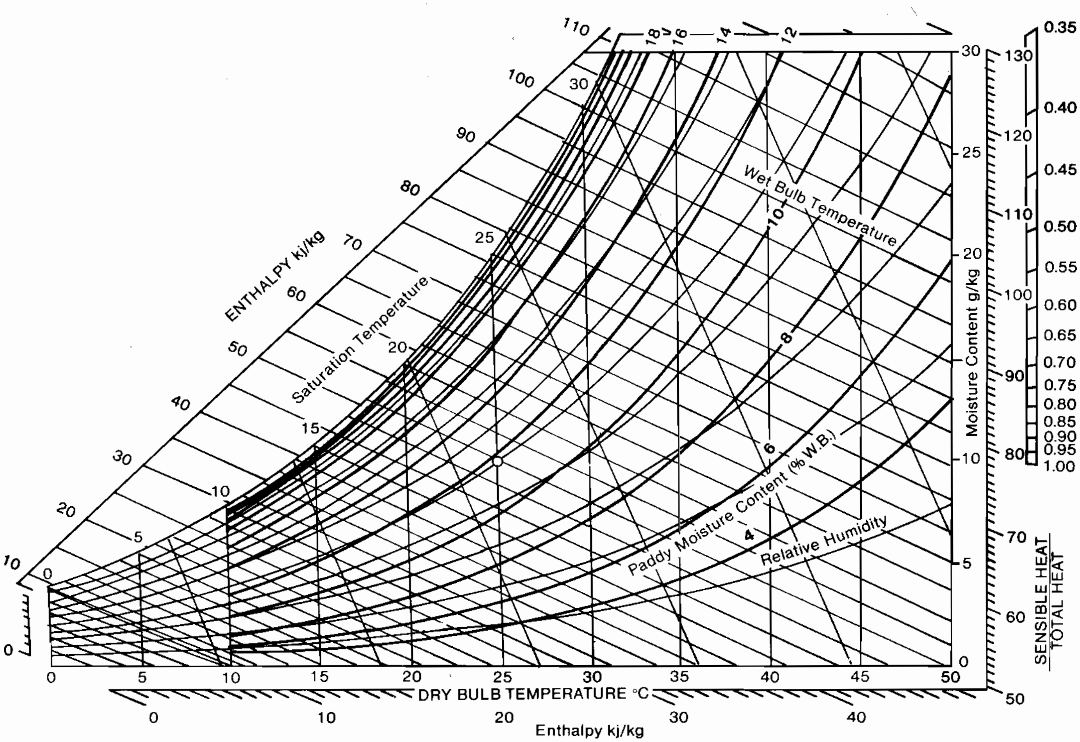

Fig. 4. Psychrometric chart showing equilibrium moisture content lines of Australian paddy rice, calculated from Putranon et al. (1979).

is the grain state in zone B calculated? After studying the physics of the behaviour of airflow through grains, the following design steps have been formulated:

(i) Assume that the moisture content in zone B is equal to the initial moisture content of the grain, i.e. the same as in zone C.

(ii) Estimate the temperature in zone B by finding the point of intersection of the inlet air wet-bulb temperature line and the initial grain moisture content line on a psychrometric chart. The dry-bulb temperature at the point of intersection is a first approximation to the temperature in zone B.

This initial estimate of the grain state in zone B is quite accurate, but it may be refined by carrying out the additional steps:

(iii) Estimate the difference in moisture contents between zones B and C, by using the rule that the moisture content difference is 1% for every 28°C difference in temperature between zones B and C, which is calculated in step (ii). If zone B is cooler than zone C then the moisture content in zone B is less than that in zone C, hence the difference in moisture is subtracted from that in zone C. If the temperature in zone B is found to be greater than that in zone C, the moisture difference must be added to that of zone C.

(iv) Refine the estimate of the temperature in zone B by using step (ii) with the grain moisture content of zone B set at that found from step (iii).

Speeds of Fronts

When designing an aeration system it is essential to be able to calculate the time it takes for the grain to be cooled. Cooling usually implies that zone C has been completely expelled from the grain, and because the front separating zones A and B moves in relative terms very slowly, most of the grain is in zone B.

As indicated in Figure 3, the front separating the zones A and B is termed a moisture front, whilst the front separating zones B and C is called a temperature front. This follows from the fact that zones B and C are of similar moisture content, but different in temperature. The grain states in zones A and B are on a line of almost constant wet-bulb temperature, but their moisture contents may be very different.

The fronts can widen as they travel through the grain because the leading edges travel faster than the trailing edges. This occurs when dry grain is cooled using air with a high relative humidity. If grain is being heated and dried the fronts do not widen, as the trailing and leading edges travel with the same velocity.

Velocities of temperature fronts and moisture fronts calculated from Sutherland et al. (1971) are shown in Figures 5 and 6. These figures apply strictly to wheat, but they represent a reasonable approximation for other cereal grains. It is clear that the speeds of temperature fronts are almost independent of grain moisture content, but the velocities of moisture fronts are very dependent on

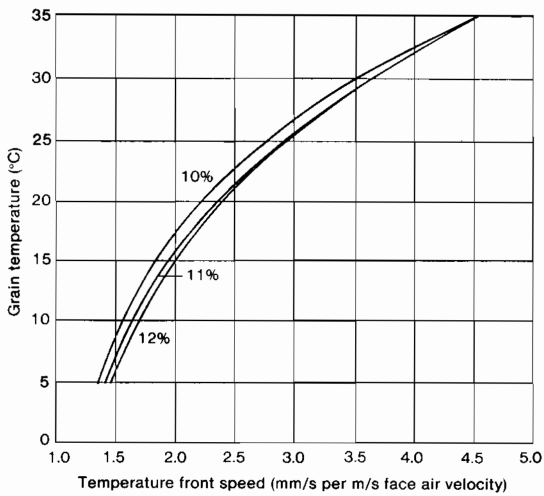

Fig. 5. Velocity of temperature fronts through wheat as a function of grain moisture content and temperature (calculated from Sutherland et al. 1971).

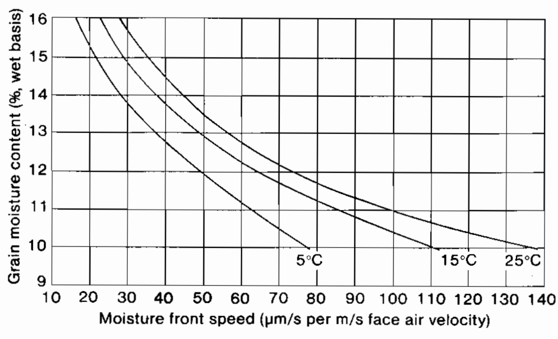

Fig. 6. Velocity of moisture fronts through wheat as a function of grain moisture content and temperature (calculated from Sutherland et al. 1971).

the grain moisture content. Grain temperature has an important influence on the speeds of both temperature and moisture fronts.

Quantifying the Benefits of Aeration

It was pointed out in the introduction that the two key variables determining the storability of grains are their temperature and moisture content. We shall now examine how manipulation of these two variables quantitatively affects storage indices such as the loss of dry matter due to respiration, insect population dynamics, seed viabilility, and the rate of pesticide decay.

Dry Matter Loss

In the hot, humid tropics grains are often harvested warm and damp. Such conditions are ideal for mould growth and unless the grain storage environment is modified by drying or cooling the grain, or both, the grain may be completely ruined within a very short time. Even under less catastrophic conditions, the loss of dry matter of the stored commodity is associated with a deterioration in quality.

Respiration may be regarded as the complete combustion of carbohydrates to carbon dioxide and water. Hexose, a typical carbohydrate, is oxidised as follows:

$$C_6H_{12}O_6 + 6O_2 = 6\,CO_2 + 6H_2O + 15778\ \text{kJ} \qquad (1)$$

This signifies that the oxidation of 1 kg of carbohydrate liberates 15778 kJ of heat, together with 1.47 kg of CO_2 and 0.6 kg of water. Thompson (1972) reports that for maize the rate of dry matter loss is time dependent and after a time θ seconds the fractional loss of dry matter (DM) is given by:

$$DM = 8.83 \times 10^{-4} (\exp (1.667 \times 10^{-6} \times \theta) -1) + 2.833 \times 10^{-9} \times \theta \qquad (2)$$

Equation 2 applies to shelled maize at 15.5°C and 25% moisture content (wet basis) with 30% damage. Because the rate of dry matter loss hence heat production varies with storage conditions, it is important to modify θ accordingly. An equivalent time, θ_{eq}, is defined thus:

$$\theta_{eq} = \frac{\theta}{M_M M_T} \qquad (3)$$

where M_M and M_T are modifiers for moisture and temperature, respectively. Expressions for M_M and M_T are reported by Thompson (1972) to be:
(a) Temperature modifier:

For $t \leq 15.5$°C or $M \leq 19\%$

$$M_T = 32.3 \exp (-0.1044t - 1.856) \qquad (4)$$

where t = grain temperature, °C
and M = moisture content, % wet-basis.

For $t > 15.5$°C and $19 < M \leq 28\%$

$$M_T = 32.3 \exp (-0.1044t-1.856) + [(M-19)/100] \exp (0.0183t - 0.28437) \qquad (5)$$

For $t > 15.5$°C and $M > 28\%$

$$M_T = 32.3 \exp (-0.1044t - 1.856) + 0.09 \exp (0.0183\,t - 0.2847) \qquad (6)$$

(b) Moisture modifier:
For $13 < M \leq 35$

$$M_M = 0.103 (\exp (455/M_{DB}\ 1.53) - 0.00845\,M_{DB} + 1.558) \qquad (7)$$

where M_{DB} = moisture content, % dry basis.

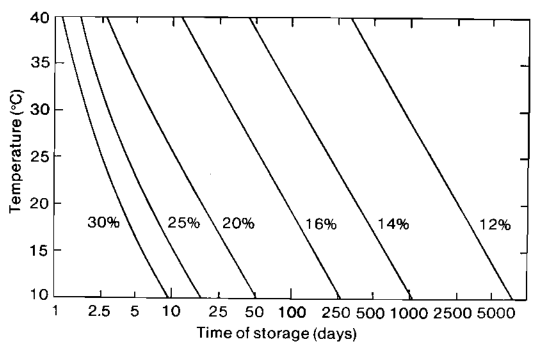

Fig. 7. Interaction of grain temperature, moisture content, and time for 0.5% dry matter of corn to be lost by respiration, calculated from Thompson (1972).

Equations 1 to 7 were used to calculate the storage conditions that give rise to 0.5% loss of dry matter. The results, shown in Figure 7, indicate that grain of 16% moisture content at 25°C, for example, loses 0.5% dry matter in about 50 days. Cooling the grain to 10°C extends the period to 250 days.

Insect Population Dynamics

The rate at which grain storage pests increase is very dependent on the temperature and moisture content of the grain. Generally, a reduction in either or both of these variables reduces the rate of insect population growth. High moisture contents and temperatures are also hostile to insect pests, but these storage conditions are best avoided as they give rise to other problems associated with moisture migration and deterioration of grain quality.

Birch (1953) carried out some of the earliest work on the population dynamics of grain storage insect pests. He used the very simple concept of weekly multiplication ratio, λ, to quantify the population growth rate of insects. He represented his data by the formula:

$$N = N_0\lambda^\theta \tag{8}$$

where N = number of insects after a time θ weeks

N_0 = initial number of insects

and λ = weekly multiplication ratio.

The value of λ is very dependent on grain moisture content, as can be seen from Figure 8 drawn for *Sitophilus oryzae*. Table 1 shows the increase in a population of *S. oryzae* after 20 weeks under various storage conditions.

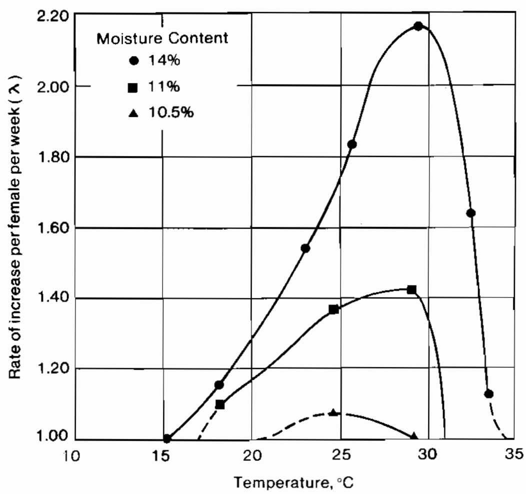

Fig. 8. The variation of weekly multiplication ratio of *Sitophilus oryzae* (small strain) with temperature and moisture content of wheat (after Birch 1953).

Seed Viability

Like insect population dynamics, the viability of seeds is also very sensitive to grain moisture content and temperature. The death of seeds follows a normal distribution, and they have a mean life, $\bar{p}$, that can be represented as a function of grain temperature, t°C, and wet-basis moisture content, m, as follows:

$$\bar{p} = 10^{K_1 - K_2 m - K_3 t} \tag{9}$$

where K_1, K_2, and K_3 relate to the kind of seed. Values of the constants reported by Roberts (1974) are given in Table 2. These data were used to calculate the half-lives of rice at various temperatures and moisture contents, and the results are shown in Table 3.

Table 1. Increase in a population of *Sitophilus oryzae* after 20 weeks under various storage conditions.

Temperature (°C)	Moisture content (%)	λ	N/N_0
26	10.5	1.06	3.2
26	11.0	1.40	837.7
26	14.0	1.86	245617.3
18	14.0	1.15	16.4
28	14.0	2.17	5360368.9
33	14.0	1.13	11.5

Table 2. Viability constants for a variety of grains and seeds, as given by Roberts (1974).

Species	K_1	K_2	K_3
Wheat (*Triticum aestivum*)	5.067	0.108	1.050
Rice (*Oryza sativa*)	6.531	0.159	0.069
Barley (*Hordeum distichon*)	6.745	0.172	0.075
Broad beans (*Vicia faba*)	5.766	0.139	0.056
Peas (*Pisum sativum*)	6.432	0.158	0.065

Table 3. Half-lives of rice under various conditions of temperature and moisture content, calculated from Roberts (1974).

Temperature (°C)	Moisture content (%, wet basis)	Half-life (days)
20	12	1750
25	12	791
30	12	357
35	12	161
40	12	73
30	9	1072
30	11	515
30	13	248
30	15	119
30	17	53

Decay of Chemical Pesticides

Chemical pesticides are often admixed with grains to combat attack by insect pests. Pesticides may be effective against the target pests for many months, can be applied to grain held in poorly constructed and unsealed stores, and require little capital expenditure for their application. Although pesticides are very inexpensive compared with the value of the commodity they protect, their cost is often the largest single component incurred during storage. When applied to warm, damp grain many chemical pesticides decompose to ineffectively low levels after only a few weeks. This can be expensive because either higher dosages must be applied in the first instance, or the grain must be retreated. Drying and/or cooling grain by aeration has a beneficial effect as it slows the rate of pesticide decay. The chemical kinetics of pesticide decay have been elucidated by Desmarchelier (1978) and Desmarchelier and Bengston (1979). It can be shown that if the initial concentration of the pesticide on the grain is C_o then the concentration C_l after θ weeks is given by:

$$C_l = C_o \exp(-1.386r\theta \times 10^{B(t-30)}/\theta^*_{1/2}) \quad (10)$$

where r = fractional relative humidity of the intergranular air, $\theta^*_{1/2}$ = half-life in weeks of pesticide on grain when r = 0.5 and the temperature is 30°C, B = a constant and t = grain temperature in °C.

Values of the constants $\theta^*_{1/2}$ and B are given in Table 4 for a number of commonly used grain protectants. Equation 10 was used to determine the effects of wheat temperature and moisture content on malathion residues after 6 months storage. The results are given in Table 5.

It was stated in the 'Introduction' that a primary aim of aeration is to reduce the heat content of the grain by either cooling and/or drying it. If this objective is achieved then aeration reduces the state of pesticide decay. Aeration also has another profound effect on the rate of pesticide decay. The general rule can be stated that aeration renders the state of decay of pesticides applied to stored grains insensitive to the initial grain state (Thorpe and Elder 1982). This means that the final concentration of pesticides on aerated grain after a given storage period is about the same even whether the grain be initially warm and wet, or cool and dry, or whatever. This is illustrated in Figures 9 and 10. It is a phenomenon of great importance to pest management.

Table 4. Half-lives of pesticides at 30°C and 50% relative humidity, and temperature coefficient B, for a variety of pesticides (after Desmarchelier and Bengston 1979)

Protectant	$\theta^*_{1/2}$ (weeks)	B (degrees^{-1})
Fenitrothion	14	0.036
Bioresmethrin	24	0.033
Bioresmethrin[a]	38	0.031
d-Fenothrin	38	0.029
d-Fenothrin[a]	40	0.029
Pyrethrum[a]	55	0.022
Methacrifos	8	0.055
Malathion	12	0.05
Chlorpyrifos-methyl	19	0.04
Carbaryl	21	0.031
Pirimiphos-methyl	70	small

[a]Plus piperonyl butoxide at 20 mg/kg

Table 5. Malathion residues on wheat held for 6 months under various conditions of temperature and moisture.

Temperature (%)	Moisture content (%, wet basis)	Final concentration of malathion / Initial concentration of malathion
30	10	0.60
30	12	0.45
30	14	0.37
30	16	0.33
20	14	0.74
40	14	0.03

Climatic Considerations and Aeration

The process of cooling grain using ambient air can be optimised by choosing to operate the aeration system when the total content of the air is lowest. This usually coincides with the time of the lowest ambient dry-bulb temperature. Even in tropical climates there is often a day-to-day variation in temperature, and this can be exploited: the air occurring during the coldest periods can be selected for aeration. For example, in Darwin, a tropical coastal city, the mean maximum and minimum daily dry-bulb temperatures during January, a monsoonal month, are 31.9°C and 25.2°C. Following a statistical procedure developed by Hunter (1981), it can be shown that ambient temperatures in Darwin during the coldest 15% of the time are 25.9°C or less; the mean temperature during this time is 24.7°C,

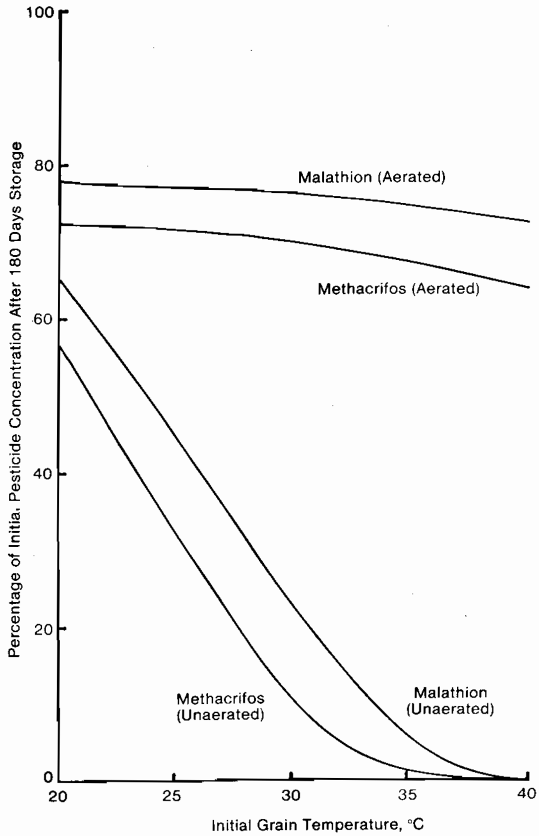

Fig. 9. Variation with initial temperature of pesticide concentration after 6 months storage of wheat initially at 11% moisture concentration under conditions of aeration and non-aeration.

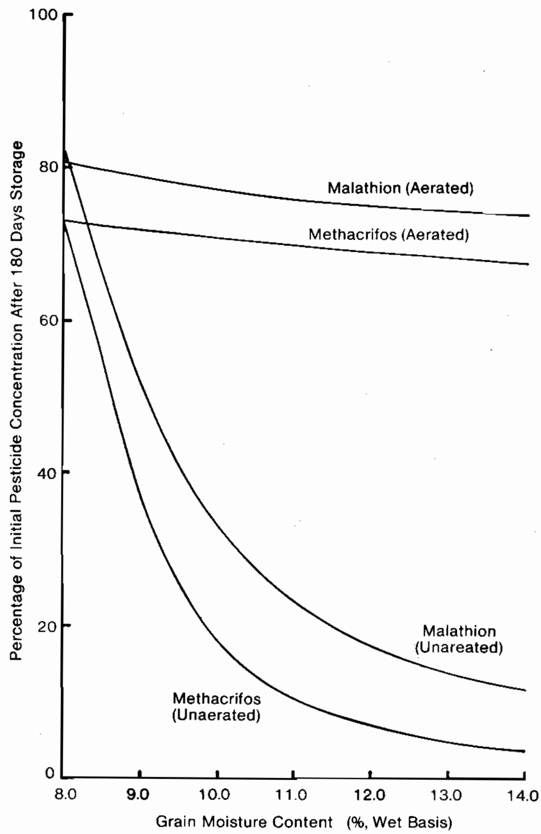

Fig. 10. Variation with initial moisture content of pesticide concentration after 6 months storage of wheat initially at 30°C, under conditions of aeration and non-aeration.

which is lower than the average daily mean maximum. Hunter (1981) shows that this information can be calculated from climatic data that includes daily mean minimum temperatures and some statistical information on the daily variability.

In the event of comprehensive weather data for a particular location not being collated and analysed, it is possible to make use of daily minimum and maximum temperatures published in local newspapers, or collected by research and educational institutions. Relative humidity data are not essential to the analysis but they help to ascertain the suitability of the climate for both grain cooling and drying by aeration. A simple method of analysing the data developed by A.J. Hunter (personal communication) relies on first calculating the following functions:

$$\gamma_H = (\mu_H - m)/\sigma_H \quad (11)$$

$$\text{and } \gamma_L = (m - \mu_L)/\sigma_L \quad (12)$$

where σ_L and σ_H are the standard deviations of the daily minimum and maximum temperatures and μ_L, μ_H and m are the mean minimum, maximum, and median daily temperatures.

The above maximum and minimum temperatures are given by:

$$\mu_H = \sum_{n=1}^{N} v_H = \frac{v_{H1} + v_{H2} + v_{H3} + ...\ v_{Hn} ... + v_{HN}}{N} \quad (13)$$

$$\mu_L = \sum_{n=1}^{N} v_L = \frac{v_{L1} + v_{L2} + v_{L3} + ... + v_{Ln} + ...\ v_{LN}}{N} \quad (14)$$

where v_{Hn} and v_{Ln} refer to the daily maximum and minimum temperatures recorded on the nth day of the month. N is the total number of days the data are available, for example, 31 in the case of May. If one has access to archives it is worthwhile calculating the statistical data for the same month over three or four years, as there are variations in climate from year to year. If four years' data were to be collected, then ideally N = 124. However, newspapers sometimes omit some data, or may not print data on one day of the week. In this case the value of N must be adjusted accordingly.

The standard deviations may be calculated from the following standard formulae:

$$\sigma_H = \left[\frac{1}{N-1} \sum_{n=1}^{N} (v_{Hn} - \mu_H)^2\right]^{1/2} \quad (15)$$

$$\sigma_L = \left[\frac{1}{N-1} \sum_{n=1}^{1} (v_{Ln} - \mu_L)^2\right]^{1/2} \quad (16)$$

Equations 15 and 16 are easy to use. Many scientific calculators have the functions built in, or the equations are easily programmed for processing on a microcomputer.

Having calculated the standard deviations, the 14 and 86 percentiles are obtained from:

$$v_{H14} = \mu_H - 1.08\sigma_H \quad (17)$$

$$v_{H86} = \mu_H + 1.08\sigma_H \quad (18)$$

Equations of identical form apply to the percentiles around the mean minimum temperature. The daily median temperature is given by:

$$m = \frac{v_{L86} + v_{H14}}{2} \quad (19)$$

The foregoing information enables an analysis of short-term temperature variability. Its use is illustrated by the example which follows:

Table 6 shows climatic data collected at a subtropical location near the coast of a large land mass. Use the analysis to comment on the suitability of the climate for both the cooling of grain by aeration for long-term storage, and for exploiting the warmest periods of the day for in-store drying of crops.

Table 6. Climatic data for a sub-tropical locality.

Day	Minimum temperature (°C)	Dew point at 0900 hours (°C)	Maximum temperature (°C)	Dew point at 1500 hours (°C)
1	15.1	16	28.3	15
2	17.9	19	33.4	18
3	18.1	19	36.2	17
4	12.9	14	25.7	14
5	11.6	13	22.6	13
6	13.8	14	24.9	14
7	16.4	17	27.1	16
8	17.7	18	31.3	17
9	17.8	18	33.7	20
10	16.1	17	30.1	17
11	16.4	17	31.8	16
12	11.1	12	21.9	11
13	11.7	12	23.6	10
14	15.1	16	27.1	14
15	15.5	16	27.9	15
16	15.3	16	27.7	15
17	16.2	18	29.0	18
18	16.6	18	31.2	17
19	17.3	19	37.1	20
20	16.5	18	27.9	19
21	17.1	18	30.8	18
22	13.2	15	27.1	15
23	11.9	13	22.2	12
24	11.3	13	21.5	11
25	13.4	14	25.6	14
26	16.9	18	31.1	18
27	17.3	18	34.7	19
28	18.2	19	37.3	19
29	18.1	19	37.2	20
30	16.4	17	34.8	18

The daily minimum temperature is found from equation 14 thus:

$$\mu_L = \frac{15.1 + 17.9 + 18.1 + \ldots + 16.4}{30}$$

$$= 15.46°C$$

and the mean maximum thus

$$\mu_H = \frac{28.3 + 33.4 + 36.2 + \ldots + 34.8}{30}$$

$$= 29.36$$

The standard deviation of temperatures about the mean minimum temperature is found from equation 16 thus:

$$\sigma_L = \{\frac{1}{29} \cdot [(15.1 - 15.46)^2 + (17.9 - 15.46)^2 + \ldots + (16.4 - 15.46)^2]\}^{1/2}$$

$$= 2.327$$

It is found that σ_H is 4.777 and

$$v_{L14} = 15.46 - 1.08 \times 2.327 = 12.95°C$$

and $$v_{L86} = 15.46 + 1.08 \times 2.327 = 17.97°C$$

$$v_{H14} = 29.36 - 1.08 \times 4.777 = 23.79°C$$

$$v_{H86} = 29.36 + 1.08 \times 4.777 = 34.93°C$$

Hence, the median temperature is $0.5 \times (17.97 + 23.79) = 20.88°C$.
It follows that $\gamma_L = (20.88 - 15.46)/2.327 = 2.33$

and $\gamma_H = (29.36 - 20.88)/4.77 = 1.78$.

Cooling is normally carried out during the night, typically during the coldest 15% of the time. From Figure 11 it is seen that when $\gamma = 2.33$ and the

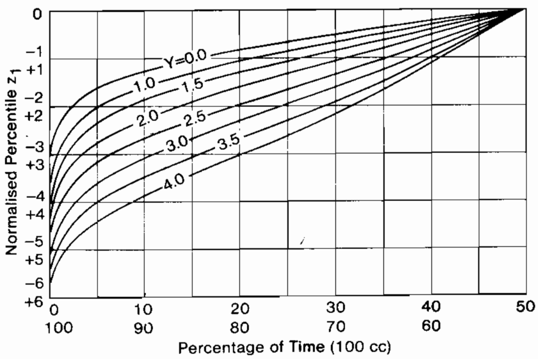

Fig. 11. Predicted cumulative distribution functions for ambient temperature as a function of γ (after Hunter 1981).

time of aeration is 15% then $z_1 = -2.15$ (the negative sign arises from the fact that the aeration occurs for less than 50% of the time). The temperature, v, below which aeration occurs is given by

$$v = m + \sigma_L z_1 \quad (20)$$

$$= 20.88 - 2.327 \times 2.15$$
$$= 15.88°C.$$

The aeration fan is turned on whenever the ambient temperature falls below 15.88°C.

To find the average temperature, $\bar{v}$, that occurs during aeration we read the value of $\bar{z}_1$ from Figure 12, and find it to be −2.8. This is then inserted into

$$\bar{v} = m + \sigma_L \bar{z}_1 \; 20.88 - 2.327 \times 2.8 \quad (21)$$
$$= 14.36°C.$$

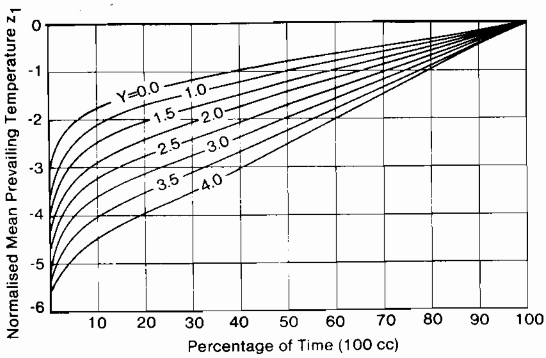

Fig. 12. Mean prevailing temperature versus percentage of time for which it is available (after Hunter 1981).

Hence, the average ambient temperature that occurs during aeration is about 14.4°C, which is less than the average minimum temperature. We see from Table 6 that at 0900 hours the dew point temperature is close to the minimum temperature, which indicates that the air used for aeration is close to saturation. Since the air is compressed in the fan, and the mass of air used for aeration is very small, the absorption of water by the grain is usually not serious.

Drying, in contrast to aeration for cooling, requires a high volume of air of low relative humidity. If the aeration fans are turned on during the warmest 50% of the time, the air above the median temperature, i.e. 20.88°C is chosen. The average temperature, $\bar{v}$, of this air is found from

$$\bar{v} = m + \sigma_H \bar{z}$$
$$= 20.88 + 4.777 \times 1.3$$
$$= 27.09°C$$

Examination of Table 6 shows that the dew point of the air when this temperature occurs is typically 15°C, which corresponds to a relative humidity of 50%. It is therefore clear that this climate is excellent for the in-store drying of grain, as well as for cooling by aeration.

Refrigerated Aeration

Ambient aeration can be very beneficial in a wide range of climates, from temperate to tropical. However, in climates with a high ambient enthalpy, aeration can be considerably enhanced by reducing the enthalpy of ambient air before admitting it to the silo. The most conventional method of doing this is by mechanical refrigeration. A solar-regenerated, open-cycle, desiccant-bed grain cooling system also shows considerable promise, although it is still at the developmental stage (Thorpe and Fricke 1985).

As Esmay, Trott, and Thorpe[1] point out, the objectives and benefits of refrigerated aeration are basically those of ambient air aeration, but under similar climatic conditions the benefits of refrigeration are more marked. These benefits are achieved with the penalty of higher operating and capital costs, but the improved marketability of the grain may outweigh the costs. Particular benefits are:

(i) The storage of damp grain under tropical conditions. It can be seen from Figure 7 that 20% moisture content grain can be stored for about 30 days with only a 0.5% loss in dry matter, provided the grain can be cooled to 15°C. This temperature cannot be achieved in climates in which the ambient wet-bulb temperature always exceeds 14°C.

(ii) The protection from insect pests in pesticide-free grain. This can be achieved by ensuring that all of a grain bulk is cooled to temperatures less than 15°C (Elder et al. 1984).

(iii) The maintenance of desirable grain quality indices such as germination, milling yield, colour, taste, and so on.

Selection of Grain Refrigeration Units

Grain refrigeration units may be built by slightly modifiying standard air conditioning equipment, or by assembling readily available air conditioning components. The most important modification to packaged air conditioning equipment is to replace the standard fan with a high-pressure fan. In a packaged air conditioning unit the standard fan normally fits into a confined space, and it is often preferable to mount an aeration fan in a separate compartment as shown in Figure 13. The main advantages of a custom-built grain refrigeration unit based on a widely used commercial air conditioner are the availability of spare parts, and the familiarity of local air conditioning mechanics with the equipment. Local refrigeration engineers may be capable of designing and assembling grain refrigeration units from standard air conditioning components such as compressors, evaporator and condenser coils, and controls. There is also the advantage of using widely available components and local expertise. Such a scheme provides local employment during both the design and construction, and maintenance phases.

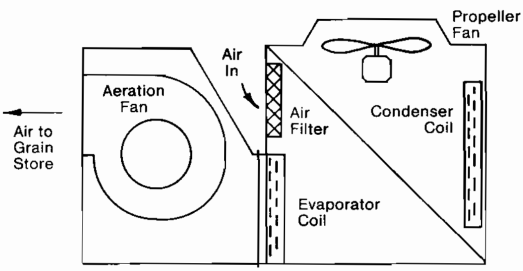

Fig. 13. Principal components of grain refrigeration unit constructed from a packaged commercial air conditioner and a separately mounted aeration fan.

It is possible to buy refrigeration units specifically designed for grain cooling, and they are fitted with suitably high pressure fans, and devices to control the relative humidity of the cooled aeration air. Such units are available in a range of capacities that are capable of cooling from 30 to 300 tonnes of grain per day. Prospective purchasers need simply specify their grain cooling needs, and the refrigeration unit suppliers will recommend complete systems. This has obvious advantages, but it must be realised that the supply of spare parts and servicing may be restricted to the particular manufacturer or its agents.

Open-Cycle, Solar-Regenerated, Desiccant-Bed Grain Cooling System

It has been pointed out that, particularly in humid tropical regions, the enthalpy (heat content) of ambient air may have to be reduced before it can be effectively used for aeration. We have seen that one method of reducing the enthalpy of ambient air is to cool it by means of refrigeration. A second method, now considered here, is to isothermally reduce the moisture content of the air.

Thorpe and Fricke (1985) have described a very simple-to-build and low energy grain cooling system, the principal elements of which are shown in Figure 14. During the air drying and cooling

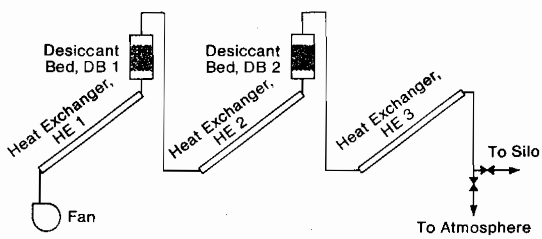

Fig. 14. Principal elements of a solar-regenerated, desiccant-bed, grain-cooling system.

process, night air from the aeration fan enters the first heat exchanger, HE1, and some of the heat of compression is lost to the atmosphere by convection and radiation to the night sky. The cool, humid air then enters desiccant bed, DB1, where it is dried iso-enthalpically. As a consequence of this process, the air increases in temperature and it is subsequently cooled in the second heat exchanger, HE2. The air is further dried in the second desiccant bed, DB2, before being finally cooled in the third heat exchanger, HE3.

The desiccant is regenerated by designing the heat exchangers HE1 and HE2 as effective solar collectors. Hence, during the day, ambient air leaving the fan is heated in the heat exchangers, thereby reducing its relative humidity so that the desiccant beds are regenerated for the night cycle.

The underlying principles of operation of the stage-wise system can be understood from the psychrometric chart (Figure 15). Cool ambient air

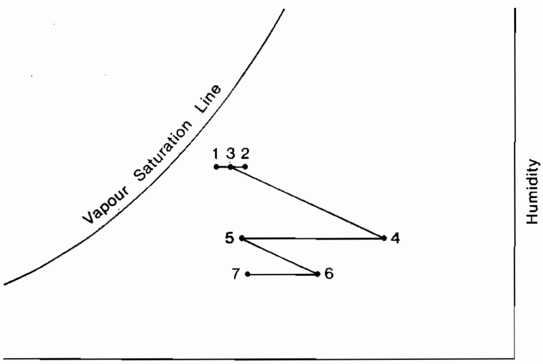

Fig. 15. Thermodynamic states of aeration air passing through a solar-regenerated, desiccant-bed, grain-cooling system.

with a high relative humidity, state 1, is compressed by the fan to state 2. It is this air that would normally be used for ventilating grain in ambient aeration systems, but because of its high enthalpy it has limited cooling capacity. In the desiccant-bed cooling system the air is cooled from state 2 to state 3 in the first heat exchanger, HE1. The air on entering the first desiccant bed, DB1, leaves at state 4, whence it is cooled by the atmosphere to state 5. Now this represents a reduction in enthalpy compared with natural aeration systems, but a further reduction is obtained by passing the air through the second desiccant bed, DB2, bringing it to state 6, before finally cooling it to state 7. It is this air that is used to cool the grain.

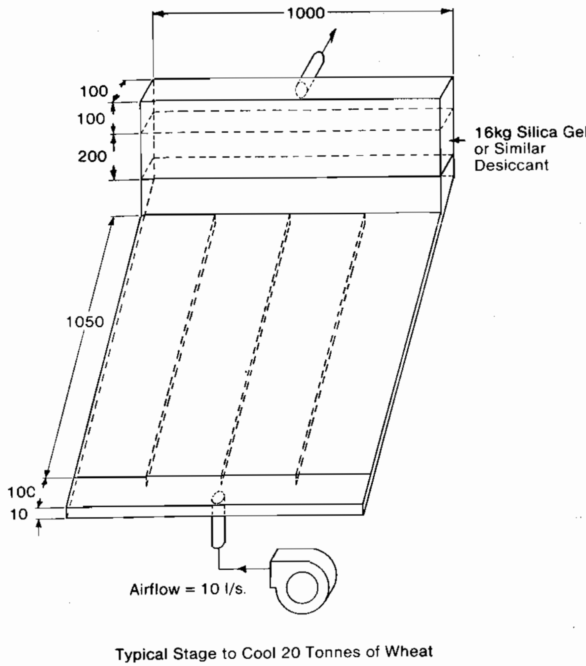

Fig. 16. An experimental, single stage of a solar grain-cooling system.

An experimental, single cooling stage is shown in Figure 16.

The system just described is still at the developmental stage. However, early computer modelling and experimental results indicate that under tropical conditions the enthalpy of ambient air can be reduced by about 20 kJ/kg. This means that grain cooled with ambient air to 26°C could be cooled to less than 20°C with air leaving the desiccant-bed system. Features of the solar-regenerated, open-cycle, desiccant-bed grain cooling system are:

- It is very simple to construct from readily available materials and its fabrication requires only basic sheet-metal working skills.
- It achieves a significant reduction in the heat content of ambient air, hence considerably lower grain temperatures can be achieved.
- Apart from a solenoid valve, it has no more moving parts than a conventional aeration system.
- It may prove possible to use renewable desiccants, such as cereal grains.

A program of work is under way in the CSIRO Division of Chemical and Wood Technology to develop the device to commercial realisation.

Simulated Performance of Solar Grain Cooler

A mathematical model of the solar grain-cooling device has been formulated, and its likely performance in preserving grains in tropical climates has been predicted. In the model, the air leaving the solar cooler was used to cool maize subject to heating by respiration. The objective of using the model was to determine an effective combination of drying with ambient air, and cooling with air modified by the solar cooler. In addition, the effects of the following strategies on storage indices such as dry matter loss, pesticide residues, insect population growth, and seed viability, were investigated: (a) taking no prophylactic action, (b) in-store drying of the grain using ambient air, or (c) drying followed by cooling.

It became apparent from the model that a high flow rate of air (about 20 litres per second per tonne of grain), is necessary to prevent serious overheating and spoilage of the grain by respiration. A suitable (though not necessarily optimum) strategy is to ventilate wet grain continuously with ambient air which a drying front has passed through the bed of grain. With an airflow rate of 20 L/sec/t this takes about 40 days, and with initially 20% moisture content maize the average dry matter loss during this period is 0.36%. Drying is then followed by cooling with an airflow rate of 1 L/sec/t. Table 7 gives details of the solar cooling system, the operating logistics, and the climatic and storage conditions. After 40 days of drying, the average grain temperature and moisture content are 26.8°C and 12.7%. After a further 142 days of cooling (a total of 26 weeks), the average grain temperature is 18.2°C, and the moisture content 12.3%.

Table 8 quantifies the effects of the three storage strategies on the grain: i.e. no prophylactic action, drying only, and drying followed by solar cooling. If no action is taken, the grain is ruined by

Table 7. Description of solar grain-cooling system and logistics investigated.

Solar Cooler	
Three unglazed absorbers, with insulation on rear of collectors.	
Dimensions of solar absorbers: 1.2 m long × 1 m wide × 0.01 m deep	
Two beds of silica gel	
Dimensions of beds of silica gel: 1 m long × 0.1 m high × 0.1 m wide	
Operational Logistics	
Drying	: 24 hours/day, 20 L/sec/t; 40 days
Cooling	: 6 hours/day regeneration of desiccant 6 hours/day aeration; 1 L/sec/t, 142 days (Total storage period 26 weeks)
Climatic Data	
Average conditions for drying	: Ambient dry bulb temperature: 23.6°C : Ambient humidity: 1.43 g/kg Solar radiation: 800 W/m^2 Temperature rise in fan: 3.23°C
Air State Leaving Solar Cooler	
Dry bulb temperature of air	: 21.1°C
Ambient humidity	: 5.9 g/kg
Initial Grain State	
Temperature	: 30°C
Moisture content	: 20% (wet basis)

Table 8. Predicted performance of combined drying and cooling system for stored grain.

Power requirement for drying	: 50 W/t
Energy consumed during drying (40 days)	: 48 kWh
Power requirement for aeration	: 1 W/t
Power requirement for regeneration	: 0.1 W/t
Energy consumed for aeration and regeneration (142 days)	: 1 kWh
Dry matter loss	
No prophylactic action	: Grain ruined by mould
Dry to 12.7% then store for total period of 26 weeks	: 0.6%
Dry to 12.7%, then cool so total storage period is 26 weeks	: 0.4%
Malathion decomposition	
No prophylactic action	: 94%
Drying then storage	: 80%
Drying followed by cooling	: 55%
Insect population growth of *Sitophilus oryzae*	
No prophylactic action	: Conditions inhospitable to insects
Drying then storage	: 200,000 × increase
Drying followed by cooling	: 20 × increase
Half-life (typical cereal grains)	
No prophylactic action	: 20 weeks
Drying then storage	: 500 weeks
Drying then cooling	: 2000 weeks

overheating due to respiration, whereas drying to 12.7% m.c. followed by storage, results in a dry matter loss of 0.6%. If the grain is cooled after drying, then the dry matter loss is only 0.4%. As expected, pesticide decay is much reduced by drying and drying followed by cooling. The latter strategy would result in 7 times less malathion (an organophosphorus pesticide) having to be applied to result in a given level of pesticide residue after 6 months storage, compared with the case in which no action is taken. The effect of drying and cooling, as opposed to drying only, is particularly marked when one considers insect population growth. Because drying leaves the grain comparatively warm (about 27°C), insects are able to proliferate very quickly. Cooling to 18°C, however, has a dramatic effect on reducing the insect population growth, such that in dried and cooled grain the insect population after 6 months is 10 000 times less than in the grain that has been dried only. A quantifiable aspect of grain quality is seed viability, and here again the benefits of drying and cooling are evident from Table 7.

Conclusions

Aeration with ambient air provides a simple, low energy method of reducing the heat content of stored grain. This has beneficial effects in so far as it can reduce the insect population pressure, preserve grain qualities such as viability, milling yield, colour, and taste, reduce the rate of dry matter loss, and reduce the rate of decay of pesticides applied to the grain. In tropical climates characterised by high ambient enthalpies, ambient aeration may be enhanced by refrigerating or desiccating the aeration air.

Acknowledgments

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Requirements for Drying High Moisture Content Grain in Southeast Asia

Dante B. de Padua*

Abstract

In spite of the recognised need, minimal use has been made of drying technology in ASEAN to prevent grain deterioration and toxin formation. In this paper, the handling of wet-harvested grain is redefined in the context of tropical Asian developing countries and the constraints to adoption of available drying technology are discussed.

One of the most serious constraints to investment in dryers is the incompatibility of system capacities with those actually required. Examples of establishing different drying systems and their technical and economic implications are presented.

In the Asian region, changes in the farming systems for rice and maize, brought about by the high-yielding, non-photoperiodic varieties, irrigated farms, and high fertiliser inputs, have resulted in increased yields and a double-cropping system.

One crop is harvested during the rainy season, when the ripe grain is reaped dripping wet with moisture contents of 24-28% of the wet weight for paddy, and over 35% for maize. There are many difficulties associated with this wet harvest. The fields are soggy, the mechanical harvesters have a tendency to clog, and the crop cannot be reaped and left in the field to cure and sun dry as traditionally practiced.

The development of a postharvest system to cope with the changes has been rather slow and many costly errors have been made in attempting to develop such a system. As a consequence we are still unable to handle the wet harvest. This has resulted in delays in stabilising the product, which lead to biochemical deterioration of the grain. This deterioration takes the form of general discoloration, yellowing, germinating, damage to milling quality, and aflatoxin contamination in maize. The yellowing of the kernels has been found to start on the farm and to begin within 24 hours of reaping, especially where field stacking the grain and straw is practiced. The phenomenon is associated with the activity of certain moulds and the spontaneous heating of the mass. Further development of grain yellowing in storage is also noted when the grain is improperly dried.

Immediate threshing and drying of the wet harvest is the only practical method to arrest deterioration. Research and development on dryer technology for the past 20 years in Asia have resulted in a better understanding of the theory and physics of forced convection, heated air drying. The functional relationships of drying air temperature and airflow rates to product milling quality, drying rates and uniformity of drying, the psychrometrics of the drying process, and the heat and mass transfer balance, have been established.

Dryers in Current Use

Drying units can now be designed, developed, and manufactured locally. During the early years of the Philippines National Food Authority (NFA), some 700 units of the small 2-tonne batch dryers developed at the University of the Philippines at Los Baños were purchased to service NFA requirements. Since then, NFA has gradually replaced its small dryers with high-capacity, continuous-flow dryers. These were also locally designed and manufactured.

Thailand has developed its own version of the batch dryer and its researchers are now promoting the technology in the countryside. For its rice complexes, Malaysia has designed and constructed 30-tonne batch dryers to complement its continu-

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ous flow dryers, and BULOG in Indonesia commissioned some 200 units of the batch dryer for their cooperatives. Local research and development has therefore led to replacement of imported units which have been found inappropriate.

One would notice, however, that the investment in heated air dryers has been made mainly by government authorities. Statistics in the Philippines indicate that only 12% of production can be handled by dryers. Most of the dryers (90%) in the country are owned by the NFA, and NFA handles only 15% of production. Obviously, the balance must be sun dried, and this is evident from the poor quality of milled rice from the wet season found in the market stalls.

Constraints to Dryer Adoption

A study made by the Philippines National Post Harvest Institute for Research and Extension (NAPHIRE) with the assistance of the International Development Research Centre (IDRC) documented the constraints perceived by both users and non-users of dryers in the private sector. There were frequent complaints against heated air forced convection dryers (often referred to somewhat imprecisely as artificial dryers or mechanical dryers) as follows:

1. Dryer capacity too great or too little for system.
   (a) 2-tonne batch dryers introduced to farmers were observed to be too large for their requirements. For example, a farmer working 3 hectares yielding 4 t/ha and with a harvesting period of one month (25 days) would have a daily drying requirement of 0.48 t, or approximately 10 bags of 50 kg.
   (b) The 2-tonne batch dryer can easily dry two loads (4 t) per day; that is, it can service 1 ha per day. This is too small for a commercial miller. The size of dryer needed by a miller is discussed later in this paper.
2. High fixed cost required and/or limited capital available.
   (a) This problem is related by farmers to their limited farm production or by millers to their procurement.
   (b) Because of the high fixed cost and limited use, it is their opinion that a dryer cannot be justified.
   (c) Within the range of farmer or processor needs, investment in a dryer has been given a lower priority.
3. High operating (variable) costs.
   (a) These are usually mentioned in comparison to direct sun drying. The high cost of oil-based fuel for the burner and engines is cited.
   (b) Dryers are therefore thought to be unprofitable.
4. It is claimed that dryers produce poorer quality milled rice than does sun drying. Higher percentages of brokens in the milled rice, darker colour, and non-uniform drying are cited.
5. Dryers are said to be inconvenient. Heat and dust are mentioned, as is having to mix the grain in some designs of batch dryer. Limited working space, particularly where the grain is handled in bags, is also perceived as a problem.

However, some of the less obvious reasons for the unsatisfactory experiences in the user of dryers may be overlooked.

1. In almost all cases, even in plants set up by business corporations, there is no realistic analysis of drying requirements in relation to the raw material supply and the plant's downstream requirements.
2. If an economic analysis is made, in most cases the assumptions are erroneous. The viability or profitability of using a dryer is analysed as a unit in isolation. The benefit is assumed to come from increased milling recovery by proper mechanical drying, but there is no increase in milling recovery compared with sun drying. The differentials in price of wet and dry paddy cannot cover the cost of drying. In the context of integrated processing plant operations, however, there is not only a penalty cost for not having drying capability but also a benefit for having it.
3. The drying phenomenon takes place so easily: add heat to air in contact with a wet product and the product dries. Nevertheless, many of the dryers sold are not properly engineered. This may result in non-uniform drying, damage to the grain and poor milling quality, inefficient heat use, dusty operations, inconvenience and unnecessary double handling.
4. Lack of operating skill. Even the best designed dryer, when operated improperly, produces disastrous results. We have cases of operators wishing to accelerate drying by raising the operating temperature. Subsequently, the paddy owner condemns the dryer for damaging his grain.

5 The benefits of having drying capability accrue not only to the direct users but also to society in general. It should be possible to show the social profitability, or even political gain for government, from allocating resources to ensure the production of better quality grain.

Advantages of Using Dryers

There are some positive observations made by users of dryers.

1. Owning a dryer provides more opportunities to procure stocks. There are fewer buyers on rainy days and farmers are therefore more willing to sell — even at lower prices — a situation where somebody's gain is someone else's loss.
2. A dryer provides for better management of a procurement program. Users can control volume of procurement, segregate varieties, and prevent mixing of different grades.
3. Users of dryers get better quality milled rice and better prices for their product.
4. They claim more efficient plant operations. The labour costs are lower and the labour problems fewer, there is less spillage, less contamination, and less handling of the grain.
5. By use of drying technology, farmer or marketing associations or cooperatives are able to provide better services to their members.

Designing Dryers for Commercial Millers

The potential users of grain drying systems are:

- large commercial farmers
- farmer cooperatives or associations
- commercial millers
- government grain marketing agencies

In the Philippines, the government handles approximately 15-20% of production. There are no large commercial rice farmers, and co-operatives or associations are still the exception. Most of the grain is handled and marketed by the private commercial millers. They are therefore the logical clients for any grain-drying research and development program.

Unfortunately, a technology that suits their requirements has not been developed. For a rice businessman, his rice mill is the heart of his enterprise. Everything else, the dryer, the warehouse, the transport facility, the by-products plant, should be designed to match the production capacity of the rice mill. There are therefore some key factors for the operation of a successful drying plant.

1. The facility should be integrated with the milling process, and considered a supportive facility. The cost of drying should be analysed as part of the integrated processing system.
2. The drying plant capacity should be compatible with the market (consumer) demands and milling requirements.
3. The operators must possess technical skills. This means not only the 'how to', but also the 'why' of things, to cope with changing product characteristics and the environment.
4. Peculiar to Asia, the drying plant should be able to handle:
   - extremely wet and dirty grain;
   - two varieties, and at least two grades, of incoming paddy;
   - batches of grain delivered to the plant with varying initial moisture contents, without mixing.

Case Study

The following example is given as a guide in establishing drying capacity needs of a commercial miller.

Example: Drying requirement for a 5 t/hour rice mill.

° For 12 hours operation/day: paddy input = 12 × 5 = 60 t/day

° For double cropping with an effective 2 months purchasing season. Total stock required = 60 × 6 month × 30 days/month.
= 10 800 t.

This assumes procuring paddy to be stored to feed the milling plant for a six-month period. Although there are only three months between harvest periods, the freshly harvested and dried paddy is cured in storage before milling. This practice is claimed to produce higher head rice yields and better cooking properties. An attempt should be made to match the volume of procurement (A) in Figure 1 to the milling requirement (B). During the rainy season harvest from August to December, procurement of volume A is possible only by using a complementary drying plant. A drying plant enables the grain businessman to keep his milling plant operating year round to meet his market requirements. It is in this context that the profitability of investment in a dryer should be analysed.

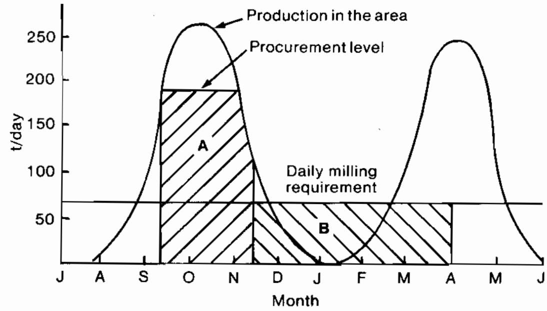

Fig. 1. Time course of harvesting of paddy showing procurement levels and daily milling requirements. During the wet season harvest, from August to December, procurement of volume A is possible only by using a complementary drying plant.

° Daily paddy procurement target

$$\frac{10\ 800\ \text{t}}{60\ \text{days}} = 180\ \text{t/day}$$

Options:

1. Continuous flow dryer (CFD) with tempering bins at the plant (Fig. 2). Four-stage multipass drying at 3% moisture content (m.c.) removal per pass or stage.

$$\frac{24\ \text{hours/day}}{4\ \text{passes/day}} = 6\ \text{hours to pass 180 t}$$

$$\frac{180\ \text{t}}{6\ \text{hours}} = 30\ \text{t/hour flow rate of paddy through dryer}$$

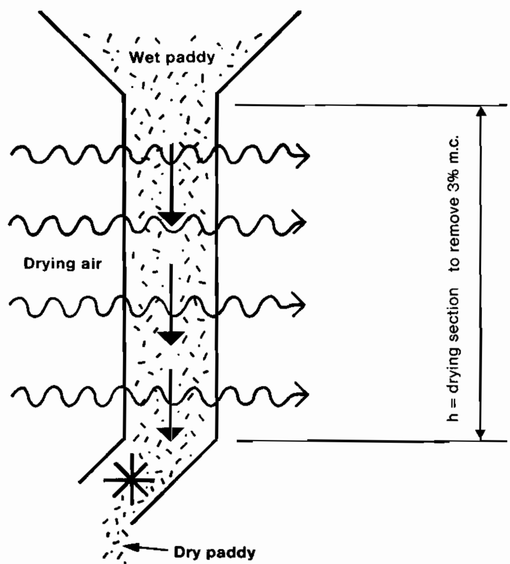

Fig. 2. Diagram of principles of the continuous flow grain dryer.

For a 30 t/hour flow rate, 45 minutes drying time for 3% m.c. drop
1 unit, 30 t/hour – 22.5 t batch capacity/unit
2 units, 15/t hour – 11.5 t batch capacity/unit
3 units, 10 t/hour – 7.5 t batch capacity/unit
4 units, 7.5 t/hour – 5.6 t batch capacity/unit
The height of unit will depend on dryer cross-section.
Note that a choice of more than one unit will give flexibility in handling different grades and varieties, but fixed costs will be higher, and so a cost/benefit study should be made of the various options.

2. Two-stage drying system.
   Stage 1. Drying at the farm level or collecting stations, to remove surface moisture from an initial 24–26% m.c. down to 18%. Several flat-bed dryers strategically located and sized to handle pre-drying.
   A flat-bed dryer with a capacity of 2 t/batch will take 4 hours to reduce m.c. from 26 to 18%. Therefore, it can dry 4 batches or 8 t/day. The system would need 22 units. Bigger capacity units could be designed to decrease the number required.

   Stage 2. Drying at plant, using CFD to dry 18–24% m.c. grain in two passes at 2% per pass.

$$\frac{10\ 800\ \text{t}}{90\ \text{days}} = 120\ \text{t/day}$$

   [At 18% m.c. drying period can be extended to 90 days]

$$\frac{24}{2} = 12\ \text{hours/drying time pass}$$

$$\frac{120}{12} = 10\ \text{t/hour flow rate of paddy through dryer}$$

   1 unit — 10 t/hour flow rate with a batch capacity of 5 t for a retention time of 30 minutes and 2% m.c. drop.

3. Stage 1. Same as option 2.
   Stage 2. In-store drying for 10 800 t. Size of facility will depend on number of days it will take to pull down m.c. from 18% to 14% without overdrying bottom layers. Comparative cost analysis is required since present warehouses are designed for bag storage.

While the computations are precise, farm production is variable from year to year, and competition for the raw material (paddy) has to be reckoned with. There are hills and valleys in the procurement of different grades. It would be useful to be able to generate information projecting cost and benefit of paddy as drying capacity increases, so as to be able to make an enlightened decision on what capacity to design for (Fig. 3).

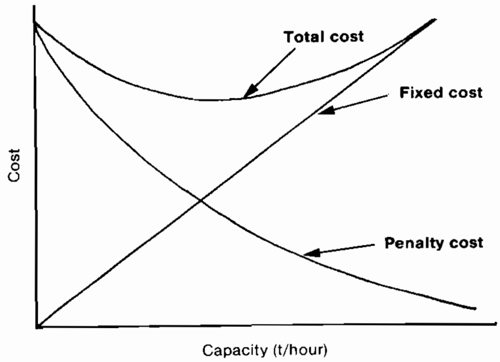

Fig. 3. How costs of grain drying vary with drying capacity.

4. Given the conditions where sun drying (when done properly) is still the cheapest form of drying, two-stage drying — artificial drying in combination with sun-drying — should be considered. How many hours and days of the harvest season can we depend on direct sun drying? An estimate based on records of average sunshine over a number of years should be made.

After assumptions have been validated and there is confidence in the estimates of drying capacity requirements, the investment decision on the type of technology will depend on technical performance and economic efficiency of the various options.

Objectives of Aeration and In-store Drying Session Chairman's Summary

R.G. Bowrey*

THE four papers in this session considered the objectives of grain drying systems and discussed some procedures which can be used to achieve these objectives.

The overall objective of grain handling was considered to be the maintenance of grain quality at a level appropriate to the end use. Certain acquired aspects of quality, such as the level of foreign material, can be improved during handling but the major intrinsic quality factors, such as head yield, discoloured grain, etc. decrease during storage and the objective of the grain handling system is to slow down the rate of quality deterioration. The fact that a large decrease in quality can occur before the grain reaches the in-store dryer was mentioned, as was the detrimental effect that fast drying can have on quality.

Two papers summarised in-store dryers used in temperature climates and the danger associated with the direct transfer of this technology to tropical climates was emphasised. This is an important area that requires further fieldwork. For high moisture grain, a two-stage drying process is most appropriate. In this system the wet grain is partly dried using high temperatures and airflow rates followed by low airflow drying and cooling. However, to achieve grain cooling in tropical regions it will be necessary to use some form of refrigeration or desiccant absorber. Such systems are successful in hot dry climates, but their use in hot humid climates will cause condensation problems if the store is not airtight.

In most humid climates supplemental heating is mandatory to dry grain in storage during the wet season and much higher airflow rates will be necessary. These flow rates must be adjusted to local weather conditions as summarised in average weather records. The advantages of pre-cleaning the grain before drying is one area requiring attention as regards handling of the wet season crop.

Grain stirrers and solar heated dryers are technically effective but are unlikely to be economically feasible.

The importance of separating aeration, which is essentially a cooling process involving sensible heat transfer, and drying, which involves latent heat transfer was stressed. Cooling grain, even without drying, is useful because it retards insect population growth and increases the useful life of pesticides.

The essence of this session is contained in the following quotes from Dr de Padua's paper.

1. Utilisation of drying technology in the ASEAN region to prevent grain deterioration has been MINIMAL in spite of the recognised need.
2. The development of post harvest systems has been slow and many costly errors made. As a consequence the problem of lack of capability to handle the wet harvest persists.
3. The benefits of drying accrue to society in general.
4. Private commercial millers are the logical clients for grain drying research and a technology developed to suit their needs is required.

The solutions to these problems lie in the technologies described during this session only if they are adapted or modified to the needs of the private millers and to the local conditions.

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Basic Principles of Aeration and In-store Drying

Physical and Thermal Properties of Grains

Do Sup Chung and Chong-Ho Lee*

Abstract

To analyse, design, and simulate grain drying and aeration systems, it is essential to have accurate information on grain physical and thermal properties such as specific gravity, bulk density, void fraction, static pressure through grains, isotherms, specific heat, thermal conductivity, heat of vaporisation, and drying rate constant.

These physical and thermal properties of grains are reviewed, particularly for rice and maize. The applicability and/or limitations of the existing data for practical or theoretical uses over a specified range of conditions are discussed. Areas in which additional research is needed are identified.

In the past three decades considerable effort has been expended to determine basic properties of food and feed grains and other agricultural products.

Knowledge of physical and thermal properties of grain is essential in solving heat and mass transfer problems involved in grain storage, drying, aeration, refrigeration, and processing.

Some of the physical and thermal properties of grain have been determined, but only at specific levels and only for particular varieties of grain. Therefore, only limited information on physical and thermal properties of grain is available.

Simulation techniques have been used to find the optimum drying conditions and to study the feasibility of natural air drying. Recent research has emphasised the need for additional data on physical and thermal properties of grain and the variation of these properties with important factors such as moisture content.

The objective of this paper is to describe the existing data on physical and thermal parameters of grain, especially of rice and corn, and discuss their applicability and limitations for practical or theoretical purposes. Also, areas in which further data are needed are identified.

Physical Property Parameters

There are many parameters related to physical properties of grain. In this section, several parameters which are closely related to the physical properties of grain, such as physical dimensions, volume, true and bulk densities, and porosity, are examined. Pressure drop through rice and corn is reviewed.

Physical Dimensions and Volume of Rice and Corn

Physical dimensions of grain, such as length, width and thickness, vary according to the variety, environmental conditions, temperature, and moisture content.

As shown in Table 1, some investigators have expressed the physical dimensions as a linear function of the moisture content of rice and corn.

It seems reasonable to present the dimensions like this because physical dimensions differ with an increase in moisture content within a certain range.

The volume of grain has been measured by using an air comparison pycnometer, or the mercury or toluene displacement methods.

Wratten et al. (1969) reported that the volume of rough rice kernels ranged from 16.06 mm^3 to 19.17 mm^3 for medium grain, and from 18.35 mm^3 to 19.66 mm^3 for long grain. Also, they expressed the volume of rough rice kernels as a linear function of the moisture content of kernel within the range from 12% to 18% moisture content. Thompson and Isaacs (1967) reported the volume of hand-shelled corn kernels ranged from 269 mm^3 to 369 mm^3. Fortes and Okos (1980) expressed the kernel volume of corn as a function of temperature and moisture content of kernel.

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Table 1. Some information related to physical dimensions of rough rice and corn.

Grain	Variety	Moisture content (%, wet basis)	Length (10^{-3}m)	Width (10^{-3}m)	Thickness (10^{-3}m)
Rough rice	Short grain Caloro	10.4 - 22.6	$7.318+1.22 \times 10^{-2}M$[a]	$3.358+8.90 \times 10^{-3}M$	$2.187+8.9 \times 10^{-3}M$
	Medium grain Saturn	12 - 18	$7.747+1.27 \times 10^{-2}M$	$2.842+7.62 \times 10^{-3}M$	$1.842+8.9 \times 10^{-3}M$
	Long grain Bluebonnet	12 - 18	$8.941+5.84 \times 10^{-2}M$	$2.388+1.65 \times 10^{-2}M$	$1.765+1.43 \times 10^{-2}M$
Corn	Pfister	6.7	16.26 (0.91)[b]	20.27 (1.07)	12.80 (0.71)
	Beck	13.96 - 21.26	13.30 (0.99)	8.7 (0.76)	4.70 (0.68)

[a] M = moisture content (%, wet basis)
[b] Numbers in parentheses indicate the standard deviation.
Sources: Goss (1965), Wratten et al. (1969), Morita and Singh (1979), Fortes and Okos (1980).

Few reports related to the volume of rice and corn were found.

True Density or Specific Gravity

True density is an important factor for heat and mass transfer analysis through grains. It can be measured by various instruments, including the pycnometer.

Because true density is moisture dependent, its values are sometimes presented as a function of moisture content. Measurements of the true density of rice and corn are given in Table 2. Investigators have devised a model to predict the true density of a certain range of moisture contents in which the measurement was conducted.

The true density of rice ranges from 1019 kg/m^3 to 1387 kg/m^3, depending on the variety and the variation in moisture content. The true density of corn ranges from 1190 kg/m^3 to about 1370 kg/m^3, depending on the variety and the variation in moisture content.

Some investigators have expressed the true

Table 2. Measurements from various sources of the true density of rice and corn.

Grain	Moisture content (%, wet basis)	True density (kg/m^3)	Models[a]
Rice			
Caloro	8.6	1358.4	
Calrose	9.2	1364.8	
Hy Mix Early	8.8	1387.2	
Rough Rice			
Short	14 - 22	1019.5 - 1037.1	1066.0 - 2.05 M
Medium	12 - 18	1324.3 - 1371.8	(1.465 - 0.0076 M)[b]
Long	12 - 18	1362.9 - 1384.0	(1.436 - 0.0042 M)[b]
Long	14 - 22	1027.4 - 1054.7	1046.1 - 1.01 M
Corn			
Pfister	6.7	1292.7	
Beck 65	21.7	1236 ± 13	
Seed	16 - 44	1293.3 - 1190.5	
Shelled	24 - 26	1369.1	$1370.0 - 0.028\left(\frac{100M}{100-M}\right)$
Yellow	9 - 27	1313.4 - 1284.5	1327.8 - 1.60 M
Yellow Dent	10 - 35	1274.5 - 1237.0	$1251.9+7.14M-0.597M^2+0.0019M^3$
Yellow Dent	12 - 23	1250.0 - 1208.1	1300.7 - 3.23 M

[a] M = moisture content (%, wet basis)
[b] Models for determing specific gravity
Sources: Goss (1965), Wratten et al. (1969), Chung and Converse (1971), Gustafson and Hall (1974), Brusewitz (1975), Fortes and Okos (1980), Kim (1980), Nelson (1980), Haque et al. (1982).

Table 3. Bulk density of rice and rough rice.

Variety	Moisture content (%, wet basis)	Bulk density (kg/m³)	Models[a]
Rice			
Caloro	8.6	571.1 (1.7)[b]	
Calrose	9.2	570.7 (6.2)	
Hy Mix Early	8.8	591.2 (9.3)	
Rough Rice			
Short	14 – 22		$537.6 + 1.22M$
Short	11 – 20	632.0 – 664.0	$583.6 + 4.27M$
Medium	12 – 18	598.3 – 648.3	$499.7 + 8.33M$
Medium	6 – 28		$567.2 + 4.13M$
Medium	13.2	590.0	
Long	12 – 18	585.6 – 615.1	$519.4 + 5.29M$
Long	9 – 11	561.0 – 598.0	
Long	13.5	710.0 – 780.0	
Long	14 – 22		$529.2 - 1.105M + 0.00995M^2$
—	—	576.7	

[a]M = moisture content (%, wet basis)
[b]Number in parentheses represents standard deviation.
Sources: Goss (1965), Wratten et al. (1969), Husain and Ojha (1969), Hosokawa and Matsumoto (1971), Agrawal and Chand (1974), Morita and Singh (1979), Vemuganti et al. (1980), Kim (1980), ASAE (1984).

density/moisture content relationship as a linear function. The linear models show that true density decreases linearly with the increase in moisture content.

In contrast to these linear models, a polynomial of the third degree with respect to moisture content was provided by Nelson (1980) to predict the true density.

Bulk Density

Bulk density, or test weight, is generally measured by using the standard apparatus recommended by the United States Department of Agriculture. Actually, bulk density is much more important than true density in drying and storage practices. Bulk density can be changed depending on the moisture content, the amount of impurities, and the degree of filling.

The bulk density of rice and corn in most experiments was measured under the loose-fill condition. The bulk density values for rice and rough rice provided by several investigators ranged from 533 kg/m³ to 780 kg/m³, as shown in Table 3.

Excluding the extreme data, other data values fluctuate between 7.5% and 18.4% around the value of 576 kg/m³ approved by the American Society of Agricultural Engineers (ASAE) for rough rice.

Wratten et al. (1969) and four other investigators reported the linear relationship between the bulk density and moisture content of rough rice within the range of moisture content they worked in. Kim (1980) used the polynomial of the third degree to represent the relationship between them.

The five linear models show that the bulk density of rough rice increases as the moisture content increases. This tendency is contrary to that of the true density of rough rice.

The bulk density of various varieties of corn is shown in Table 4. These values, which come from various sources, range from 448 kg/m³ to 789 kg/m³. Except for the bulk density values for husked ear corn and green sweet corn, the variation of the bulk density remains within the range of about 10% of 717.6 kg/m³, which is the bulk density approved by the ASAE for shelled corn.

Vemuganti et al. (1980) reported that the bulk density and moisture content of flint corn and dent corn have the linear relationship. On the other hand, Brusewitz (1975) and Nelson (1980) expressed their relationship by using a polynomial of the second or higher degree. Also, Brusewitz (1975) commented that bulk density of seed corn reached a maximum value at around 30% moisture content.

However, in contrast to the trend of the values of bulk density for rough rice, the linear models for flint and dent corn show that bulk density of corn decreases with an increase in moisture content.

Table 4. Bulk density of corn.

Variety	Moisture content (%, wet basis)	Bulk density (kg/m³)	Models[a]
Pfister	6.7	744.5 (8.6)[b]	
Shelled	7 - 25	752.9 - 656.8	
Shelled	—	717.6	
Flint	6 - 28	789.1 - 644.8	828.5 - 6.56M
Dent	6 - 28	779.0 - 635.5	818.1 - 6.52M
Yellow Dent	10 - 35	742.2 - 638.5	$682.9+14.22M - 0.9843M^2+0.01548M^3$
Yellow Dent	12 - 23	784.3 - 698.4	
Seed	16 - 44	734.1 - 710.3	$1086.3 - 2.97M + 4.81M^2$
Ear Husked	—	448.5	
Green Sweet	—	448.5	

[a]M = moisture content (%, wet basis)
[b]Number in parentheses represents standard deviation.
Sources: Goss (1965), Brusewitz (1975), Nelson (1980), Vemuganti et al. (1980), Haque et al. (1982), ASAE (1984).

Porosity

Porosity changes depending on the bulk density, the degree of filling, the amount of foreign material, the amount of fine material, and the moisture content of the grain.

Porosity can be determined by using the ratio of bulk density to true density values.

Gustafson and Hall (1972) reported a linear relationship between porosity of corn and its test weight. Chung and Converse (1971) represented the porosity of yellow dent corn as a linear function of bulk density.

Wratten et al. (1969) and one other investigator expressed the porosity of rough rice as a linear function of moisture content rather than bulk density or test weight.

In this case, the degree of filling, which affects porosity, is not considered.

Therefore, it seems reasonable to represent porosity as a function of bulk density, which is

Table 5. Porosity values of rice and corn.

Grain	Moisture content (%, wet basis)	Porosity (%)	Models[a]
Rice			
Honduras	11.9	50.4	
Wateribune	12.4	46.5	
Rough Rice			
Durar	11.4	51.0	
Taichung	9.3	52.0	
Kalinpong	9.7	54.5	
Short	14 - 22	46.4 - 47.6	49.7 - 0.227M
Medium	12 - 18	58.5 - 53.1	65.6 - 0.475M
Medium	13.2	52.5	
Long	12 - 18	59.6 - 56.9	69.5 - 0.885M
Long	14–22	48.4 - 50.8	$49.4+0.064M-0.0099M^2$
Corn			
No. 1	9.0	40.0	
Yellow	25.0	44.0	
Yellow	9 - 14	38.5 - 47.6	
Yellow	9 - 27		$101.0 - 0.078D_b$
Shelled	9 - 31	38.5 - 47.6	
Yellow Shelled	9 - 27		$81.4-0.056W_t$
Yellow Dent	12 - 23.4	37 - 42	
Yellow Dent Shelled	15.0	40.0	

[a]M = moisture content (%, wet basis), D_b = bulk density (kg/m³), W_t = test weight (kg/m³)
Sources: Thompson and Isaacs (1967), Wratten et al. (1969), Hosokawa and Matsumoto (1971), Chung and Converse (1971), Gustafson and Hall (1972), Agrawal and Chand (1974), Kim (1980), Haque et al. (1982).

moisture dependent. According to Wratten et al. (1969), the porosity of rice and rough rice ranges from 46% to 60% and decreases linearly with an increase in moisture content.

Excluding the data of Wratten et al. (1969), other data vary within a narrow range, that is, 46% through 54% (Table 5). There is little difference between these data and the value approved by the ASAE for rice.

The few data available on porosity of corn indicate that it ranges from 38.5% to 47.6%, regardless of variety and moisture variation. The porosity values of corn approved by the ASAE fall within this range. It seems desirable for the amount of fine materials to be regarded as an important factor when expressing porosity as a function of other parameters such as bulk density and moisture content.

Static Pressure Drop

Having exact information about the pressure drop for airflow through grain is very important in designing dryer or aeration systems as well as in choosing the correct fan. The pressure drop for airflow through grain depends on the airflow rate, the surface and shape characteristics of grain, the number, size and configuration of the voids, the variability of the particle size, and the bed depth.

Also, pressure drop is influenced by the extent of packing and the amount of foreign material. Brooker et al. (1974) reported that as the percentage fines in the mixture increases, the resistance pressure increases.

Haque et al. (1982) and Chung et al. (1985) investigated the effect of the moisture content of grain on resistance to airflow. They reported that the static pressure drop through grain increases with an increase in airflow rate as well as air velocity, and that moisture content of grain significantly affects the pressure drop.

Hukill and Shedd (1955) developed a model to predict the pressure drop over an airflow range of 0.01 through 0.20 m³/s.m², and determined the constants involved in the equation for several grains.

Their model was revised and approved by the ASAE Committee on Technical Data.

$$\frac{P}{L} = \frac{a\,Q^2}{\ln(1+bQ)} \qquad (1)$$

where, P = static pressure (Pa)
L = bed depth (m)
Q = airflow rate ($m^3/s.m^2$)
a, b = constants

Haque et al. (1978) and Chung et al. (1984, 1985) expressed the static pressure or pressure drop as a polynomial of the second degree of airflow rate, moisture content of grain, and the percentage of fines present (Figs 1 and 2).

Models devised by several investigators to determine the static pressure drop for rice and corn are illustrated in Table 6. It can be seen that these models include only a limited number of parameters among several which may affect the static pressure drop such as airflow rate, bed depth, density, moisture content, the amount of fine materials, the degree of filling, and particle size.

In order for these models to be used for simulation work on drying and aeration systems,

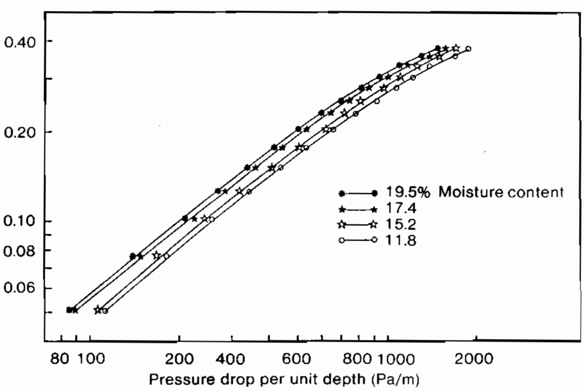

Fig. 1. Plots of airflow versus pressure drop for rough rice at various moisture contents (wet basis) and containing 5% foreign material.

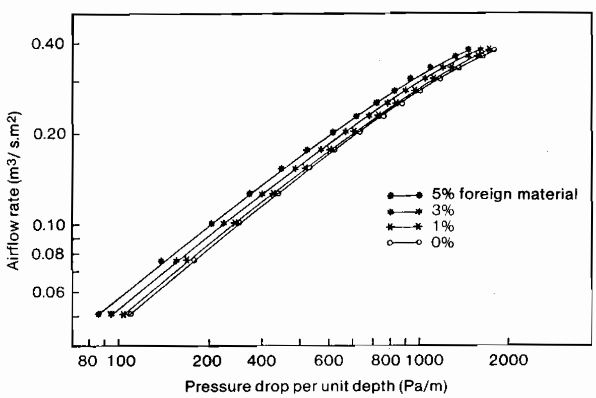

Fig. 2. Plots of airflow versus pressure drop for rough rice at 19.5% moisture content (wet basis) and containing various amounts of foreign material.

Table 6. Some models for determining pressure drop or static pressure, and airflow rate

Model	Parameters	Value of constants
Gunasekaram et al. (1983) $\ln(Q)=a(\ln \Delta p)^2+b\ln(\Delta p)+c$	Q = airflow rate ($m^3/s.m^2$) p = pressure (Pa/m) moisture content (12.8%, wet basis) bed depth (5 - 30 cm)	Rough rice (long grain) a = − 0.031 b = 0.092 c = −3.024
Haque et al. (1978) $\Delta p=C_1Q_a+C_2Q_a^2+C_3Q_a(FM)$	Δp = pressure drop (Pa/m Q_a = airflow rate ($m^3/s.m^2$) (0.076 - 0.381) FM = % foreign materials (0-20) bed depth (45.72 cm)	Yellow dent corn C1 = 436.67 C2 = 7363.04 C3 = 22525.82
Haque et al. (1978) $\Delta p=AV+BV^2-CMV$	Δp = pressure drop (Pa/m) V = air velocity (m/s) M = moisture content (%, wet basis) (12.4 - 25.3)	Yellow dent corn (clean loose-fill) A = 1611.7 B = 4949.3 C = 55.1
Husain and Ojha (1969) $Ps=(mD+c)A^{oD+e}$	Ps = static pressure (mm H_20) D = bed depth (cm) Q = airflow rate ($m^3/min.m^2$) (1 - 6) moisture content (13.5%, wet basis)	Rough rice m = 0.322 c = −1.32 D = 2.14 e = −0.0089
Shedd (1945, 1951) $Q = a\frac{P^b}{D^c}$	Q = airflow rate (cfm/ft²) (10 - 70) P = pressure drop (inch H_20) D = bed depth (ft) (2 - 8)	Shelled corn with impurities (20% w.b.) a = 150 b = 0.564 c = 0.646 Cleaned shelled corn a = 303 b = 0.422 c = 0.542
Chung et al. (1984, 1985) $SP=A(AF)+B(AF)^2$ $-C(AF)(MC)-D(AF)(FM)$	SP = static pressure (Pa/m) AF = airflow rate ($m^3/s.m^2$ (0.0508 - 0.381) MC = moisture content (%, wet basis) (11.8 - 19.5) FM = % fine material (0 - 8)	Rough rice (long grain) A = 3749.15 B = 8289.97 C = 117.12 D = 164.23

further research is needed to develop models including as many as possible of the parameters which affect the pressure drop for airflow through grain.

Thermal Property Parameters

A knowledge of the thermal properties of grain is essential when studying the problems encountered in drying and storage of grain in bulk. In this section, specific heat, thermal conductivity, isotherms, and heat of vaporisation are reviewed.

Specific Heat and Thermal Conductivity

Various methods have been used to determine specific heat and thermal conductivity of rice and corn. The usual approach in these studies is to determine the relationship between these values and moisture content.

The ASAE (1984) has approved four linear regression equations for calculating specific heat and one for calculating thermal conductivity of rice. The ASAE (1984) also approved seven numerical values for specific heat of corn at specified moisture levels and an equation for determining the specific heat at other moisture levels.

Specific heat and thermal conductivity values of rice and corn are summarised in Table 7. These values and equations were orginated from research works conducted by Haswell (1954), Kazarian and Hall (1965), and Wratten et al. (1969).

Regardless of variety, the values of specific heat of rice range from 1.3 to about 2.0 kJ/kg.K

Table 7. Specific heat and thermal conductivity values for rice and corn approved by the American Society of Agricultural Engineers

Grain	Moisure content (%, wet basis)	Mean temperature (K)	Specific heat (kJ/kg.K)	Thermal conductivity (W/m.K)
Rice, rough	10.2 – 17.0		1.1095+0.0448M[a]	
Rice, shelled	9.8 – 17.6		1.2016+0.0381M	
Rice, finished	10.8 – 17.4		1.1807+0.0377M	
Rice, rough, medium	10.0 – 20.0		0.9214+0.545M	0.0866+0.001327M
Corn, yellow, dent	0.9	293.7	1.5324	0.14055
	5.1	293.7	1.6915	0.14661
	9.8		1.8338	0.15198
	13.2			0.17656
	14.7	293.7	2.0264	0.15908
	20.1	293.7	2.2232	0.16358
	24.7		2.3739	0.16998
	30.2	293.7	2.4618	0.17240
	0.68 – 20.3	308.4	1.4654+0.0356M	0.1409+0.00118M

[a]M = moisture content (%, wet basis)

depending on the variation of moisture content approximately 10% to 20% wet basis.

The values of specific heat of corn range from 1.5 to 2.5 kJ/kg.K with an increase in moisture content from about 10% to 30% wet basis at approximately 294K.

The values of thermal conductivity of rice range from 0.86 to 1.8 W/m.K, depending on the variety, the initial temperature, measuring methods, and moisture content of grain.

Fortes and Okos (1980) expressed the thermal conductivity of corn as a function of moisture content and temperature, whereas Wratten et al. (1969), Morita and Singh (1979), and Haswell (1954) described it as a function of moisture content.

Kim (1980) reported that the thermal conductivity of rough rice is affected by porosity.

Adsorption and Desorption Isotherms

The accuracy of equilibrium moisture content equations is important for successful modelling and optimisation of grain drying and aeration system design. A number of theoretical, semi-theoretical, and empirical models have been proposed for predicting the moisture equilibria of cereal grains.

Some of these models have been tested for their accuracy and applicability by other investigators. Some of them are applicable within limited ranges of relative humidity, and in either the adsorption or desorption phase.

Many references have focused on the desorption phase rather than the adsorption phase. Few models are capable of accurately describing equilibrium moisture content at a relative humidity above 90%. It is known that this difficulty is caused by condensation on the grain sample, or mould development during the experimental process, especially when static methods are being used.

Zuritz et al. (1979) therefore suggested that a dynamic method is more desirable than a static one for experiment work on isotherms at levels of relative humidity above 87%. Vemuganti and Pfost (1980) also suggested that the equilibrium relative humidity method can be used in this situation.

Among the several equilibrium moisture content models, four well-known ones are the BET equation, the Smith equation, the modified Henderson equation, and the Chung-Pfost equation. The Chung-Pfost and modified Henderson models were recognised as being more accurate than other equations over a wider range of relative humidity, and for various cereal grains.

These two equations and their constants for rough rice and yellow dent corn (approved by the ASAE) are shown in Table 8.

Table 8. Equilibrium moisture content equations and constants approved by the American Society of Agricultural Engineers

Equation[a]	Constants	Grain	
		Rough rice	Yellow dent corn
Modified Henderson equation			
$M = \frac{1}{100}\left[\frac{\ln(1-RH)}{-K(T+C)}\right]^{1/N}$	K	1.9187	8.6541
	N	2.4451	1.8634
$RH = 1 - Exp[-K(T+C)(100M)^{N}$	C	51.161	49.810
	SEM[b]	0.0097	0.0127
Chung-Pfost equation			
$M = E - F\ln[-(T+C)\ln(RH)]$	A	594.61	312.40
	B	21.732	16.958
$RH = Exp[\frac{-A}{(T+C)} Exp(-B\,M)]$	C	35.703	30.205
	E	0.29394	0.33872
	F	0.0046015	0.058970
	SEM[b]	0.0096	0.0121

[a]M = grain moisture (decimal, dry basis)
RH = relative humidity (decimal)
T = temperature (°C)

[b]SEM = Standard error moisture

Heat of Vaporisation

The heat of vaporisation of water in rice and corn is defined as the energy required to vaporise moisture from the grain.

Equilibrium moisture content curves furnish the data necessary to calculate the heat of vaporisation for moisture.

Therefore, the accurate calculation of the heat of vaporisation depends entirely upon the correct choice of equilibrium moisture content data appropriate to the specific situation.

Othmer (1940) devised a convenient method to determine the latent heat based on the vapour pressure. It has been widely used because it is quite simple and useful for agricultural crops.

Gallaher (1951) described the ratio of latent heat of wheat to latent heat of free water as an exponential function with respect to moisture content.

Rodriguez et al. (1963) tested three equilibrium moisture content models such as Clausins-Clapeyron equation, Othmer equation, and BET equation after calculating the heat of vaporisation for shelled corn at 30°C through 50°C and identified the applicability of these models.

Also, they reported that the heat of vaporisation of shelled corn decreases with an increase in moisture content and approaches that of free water at high moisture contents.

Bekker and Sallans (1956) derived an equation for the differential net heat of desorption based on Othmer's method and tested the BET and Smith equations.

They concluded that the Smith equation is not reliable beyond the relative vapour pressure of 0.95, which is corresponded to about 30% moisture content at 50°C.

Johnson and Dale (1954) reported that the heat required for vaporisation of water in wheat and corn is between 1.00 and 1.06 times that for vaporisation of free water above 12.3% moisture content (wet basis), and the heat requirement is further increased below 12.3% moisture content (wet basis).

Chung and Pfost (1967) reported that the isosteric heat in the desorption and adsorption phases fell from 3508 to 2484 kJ/kg and from 3070 to 2470 kJ/kg, respectively, and the net heat of vaporisation from 1098 to 74 kJ/kg for desorption and from 658 to 60 kJ/kg for adsorption, moisture content ranging from 4 to 20% at 31°C.

They concluded that the net heat of sorption approaches zero as the moisture content increases, a conclusion also drawn by Johnson and Dale (1954).

Table 9. Variation of the ratio of latent heat of corn to latent heat of free water by moisture content and temperature

Moisture content (%, wet basis)	Temperature (°C)				
	0	10	21.1	37.8	65.6
10	1.177	1.174	1.175	1.176	1.171
11	1.135	1.136	1.137	1.138	1.131
12	1.093	1.094	1.095	1.095	1.096
13	1.065	1.066	1.066	1.066	1.062
14	1.042	1.042	1.043	1.041	1.042
15	1.019	1.019	1.019	1.017	1.017

Source: Thompson and Shedd (1954)

Thompson and Shedd (1954) investigated the heat of vaporisation of corn and wheat by Othmer's method and concluded that for corn and wheat it decreases with an increase in moisture content as well as temperature, as shown in Table 9.

There are few numerical data on the heat of vaporisation of rice. It seems desirable to devise, for practical use, some equations for calculating heat of vaporisation directly from moisture and temperature information, such as the equation derived by Chung and Pfost (1967).

Drying and Rewetting Rates

The accurate prediction of the drying and rewetting behaviour of deep beds of grain depends directly on the accurate description of the thin-layer process, under the assumption that the deep bed is composed of a series of thin layers.

A number of investigators have therefore tried to develop successful thin-layer drying and rewetting models for grain, especially for shelled corn. Each has developed an equation from their own data obtained under conditions of interest to them.

Thompson et al. (1968) developed a mathematical drying model to predict the performance of various types of grain dryers.

Chittenden and Hustrulid (1966) presented a method for describing and predicting the drying curves for single corn kernels under conditions of known air temperature, air relative humidity, initial corn moisture content, and kernel size.

They determined that the drying rate constant is related to the effective moisture diffusion coefficient and the effective kernel radius.

Flood et al. (1972) studied thin-layer drying and rewetting equations for a natural-air corn drying system and fixed the constants involved in their equation through some tests.

On the other hand, Troeger and Hukill (1971) developed a mathematical model for the drying rate of fully exposed corn on the basis of the diffusion law and determined their constants in terms of test variables.

Also, Sharaf-Eldeen et al. (1980) developed a model for fully exposed ear corn drying by using the general form of the solution to the diffusion equation and determined drying parameters.

They commented that their model should be beneficial in describing bulk drying of ear corn. Thompson et al. (1968), Hall (1971), Flood et al. (1972), Misra and Brooker (1980), and Li and Morey (1984) used equilibrium moisture content (M_e) when defining the moisture content ratio (MR). However, Hustrulid and Flikke (1959) and some other investigators introduced the dynamic equilibrium moisture content (M_s) rather than equilibrium moisture content (M_e) into models for determining drying rate of the thin-layer drying.

Misra and Brooker (1980) conducted their own experimental work for shelled yellow dent corn and compiled all useful data on thin-layer drying and rewetting in the temperature range of 2.2°C to 71.1°C from other sources.

They identified the following model as the most promising one through the preliminary analysis, then expressed the drying constants K and N as a function of air temperature (T), air humidity (H), air velocity (V), and the initial moisture content (M_o).

$$MR = \frac{M - M_e}{M_o - M_e} = \text{Exp}\,[-\,Kt^N] \qquad (2)$$

where

MR = moisture content ratio
M = moisture content (%, d.b.)
M_e = equilibrium moisture content (%, d.b.)
t = time.

Through the statistical analysis of the combined

Table 10. Drying constants for yellow dent corn.

Drying constants	K	N	R^2
Model I:	$K = \text{Exp}\,[-a+b\ln(1.8T+32) + CV]$	$N = d\ln(H)+eM_0$	
Drying	a = 7.1735 b = 1.2793 c = 0.1378	d = 0.0811 e = 0.0078	0.967
Rewetting	a = 8.5122 b = 1.2178 c = 0.0864	d = 2.1876 e = −0.0167	0.991
Model II:	$K = a + bT + cT^2$	$N = d + eT + fT^2$	
Drying (1)	$a = 2.216 \times 10^{-2}$ $b = 1.113 \times 10^{-4}$ $c = 3.435 \times 10^{-6}$	$d = 0.5409$ $e = 1.498 \times 10^{-3}$ $f = 2.561 \times 10^{-6}$	0.997
Drying (2)	$a = 1.026 \times 10^{-2}$ $b = 2.651 \times 10^{-4}$ $c = 2.820 \times 10^{-6}$	$d = 0.6057$ $e = 1.568 \times 10^{-4}$ $f = 9.601 \times 10^{-6}$	0.981
Model III:	$K = a + bT^2 + cTM_0$	$N = d + eM_0^2 + fT^2$	
Drying (3)	$a = 1.091 \times 10^{-2}$ $b = 2.767 \times 10^{-6}$ $c = 7.286 \times 10^{-6}$	$d = 0.5375$ $e = 1.141 \times 10^{-5}$ $f = 5.183 \times 10^{-5}$	0.975

T = air temperature (K), V = air velocity (m/s), H = air humidity (%), M_0 = initial moisture content (%, dry basis)
Sources: Misra and Brooker (1980), Li and Morey (1984).

data obtained from their own and other investigators' experimental work, they determined the values for the drying constants K and N shown in Table 10.

They concluded that drying air temperature and the air velocity significantly affect the parameter K in the drying phase equation, and the air temperature and the initial moisture content significantly affect the parameter K in the thin-layer rewetting equation.

On the other hand, Li and Morey (1984) determined the drying constants K and N for yellow dent corn harvested in two consecutive years, by an approach similar to that used by Misra and Brooker (1980).

After testing the effect of drying air temperature, airflow rate, initial moisture content, and relative humidity on thin-layer drying rate, they concluded that drying air temperature had the greatest effect on drying rates, and airflow rate and relative humidity had smaller effects.

In addition to the above, they suggest that relative humidity can probably be neglected when developing thin-layer models for use in deep-bed drying simulation.

Few studies have focused on drying and rewetting rates in corn drying. Similarly, there are few references to drying and rewetting constants or rates for rice or rough rice.

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The Application of Psychrometrics to Grain Aeration

Robert H. Driscoll*

Abstract

Current research on the dynamic relationship between air and grain properties is reviewed. Weather patterns for typical grain crop areas are considered in terms of relative humidity and temperature. There is a conflict between the economic benefits of drying grain slowly and the quality benefits of drying grain quickly. The optimum balance between the two should be sought. For example, for tropical conditions it is essential to dry high-moisture grains to a lower moisture content immediately. Great advances have recently been made in our understanding of grain/air equilibrium, yielding more accurate models of the isothermal behaviour of grain in contact with air. Such models are of great importance in developing accurate grain-drying models for use in simulation studies of grain-drying.

Daily profiles of relative humidity and temperature demonstrate that, for near-ambient drying methods, consideration of the time of day is of great importance in developing an economical drying strategy. During daylight, there is a substantial drop in relative humidity, and the ambient air is better for removing moisture. Various slow-dryer management systems are considered from the point of view of air usage, especially time control and relative humidity control. Convenient methods for representing and visualising grain drying in terms of psychrometric charts have provided simple methods of studying drying strategies. Single-grain drying, thin-layer drying, and deep-bed drying can all be represented, and charts of equilibrium front speeds allow quick estimates of drying times to be made for a range of conditions.

CONSIDERABLE research has been directed towards the problem of removing moisture from grains in tropical and subtropical climates, as evidenced by work by Renwick (1984) in Indonesia, Wahab and Dhiauddin (1984) in Malaysia, and Brooker et al. (1974) in America, and work on developing computer simulation models, as for example that of Bowden et al. (1983). The vast majority of the world's rice crops are grown in hot, humid climates where drying of the grain after harvesting is difficult. Traditionally, sun-drying is used as the solution, involving spreading the grain in thin layers on concrete or on the roadside in order to gain maximum drying benefit from the radiant and convective heat of the sun. This method is still the most commonly used method for drying crops in the world today. However, the method suffers from serious quality problems, such as sunchecking and discoloration, and is not a sufficiently effective drying technique for the wet season (Mendoza et al. 1981). Many areas of the tropics are now moving towards increased grain production in the dry season, for harvest during the wet season, aided by the introduction of irrigation systems. The increased land utilisation is a vital step towards grain self-sufficiency for these countries.

This trend has enormously increased the grain drying load in Southeast Asia. There is growing concern over the high proportions of grain lost due to quality problems during the wet season (Wahab and Dhiauddin 1984). The requirement of increased technology to handle the problems generated by the wet season harvest has led to new research interest in the relationship between psychrometrics and drying theory.

The following paper reviews progress in the understanding of the interactions between air and grain (Brooker et al. 1974). The areas of moisture movement in grain, and heat and mass transfer in grain drying have been avoided, being areas more relevant to forced convection modelling and grain properties. Therefore, the main emphasis is on the application of psychrometrics to the grain-drying problem, using models of grain properties from the literature without explanation or development.

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More detail can be found in reviews such as that of Sharp (1982).

The presentation has been structured as follows. Firstly, the interaction between air and grain moisture is considered for the equilibrium situation. The concepts of moisture content levels, isotherms, equilibrium relative humidities, and forms of equilibrium are prerequisites to air/grain studies, and great advances in our understanding in these areas have been made. The manner in which a grain loses its moisture is then considered, looking at the theory of two-stage drying curves, psychrometric drying plots, critical air speeds, and current models of the thin-layer drying curve. This theory is then applied and extended to a stationary deep bed, considering the drying advantages of a deep bed and the concept of moisture and enthalpy fronts. Variations in weather properties are analysed as regards their effects on an aerated grain mass. Finally, there is an overview of drying strategies, including those involving time of day and relative humidity control.

Air/Grain Equilibrium

The moisture equilibrium characteristic for a particular grain species constitutes one of the two most vital thermodynamic properties of the grain as regards drying (Driscoll and Adamczak, unpublished report; Dung et al. 1980; Pixton 1983). The other is the rate of moisture loss of a thin layer of grain in an airstream of known temperature and humidity. The equilibrium moisture content of a food product may be expressed as a function of three variables, the atmospheric relative humidity, the product temperature, and the moisture history of the product. The last factor leads to effects such as hysteresis.

Grain is a hygroscopic material (Karon and Adams 1949), so a sample of grain will adsorb or release moisture in such a way as to come to equilibrium with its surrounding environment. Observations of the approach to equilibrium led many early researchers to the concept of dynamic moisture equilibrium, a concept since refuted by more detailed studies (Bakker-Arkema and Hall 1965). The approach to equilibrium is limited by the moisture transfer rate within the kernel (Pixton and Warburton 1968), discussed later. For a given temperature, the air relative humidity can be plotted against the moisture content of the product, by conditioning the grain gradually to different relative humidity environments and measuring the grain moisture content after equilibrium is reached. This moisture content is called the equilibrium moisture content, and the resulting plots are isotherms (Labuza 1968). Many models have been developed to describe the relationship between relative humidity and product moisture content, based on physical theories of moisture transfer or on empirical models but, because of the many different physical mechanisms involved, none is generally applicable. Examples are the BET isotherms (e.g. Day and Nelson, 1965) for low relative humidities and the Langmuir isotherms for higher relative humidities. In practice, due to the inadequacies of the physical theories, grain researchers have tended to develop their own semi-empirical models, applicable over their range of interest (e.g. Sutherland et al. 1971; Putranon et al. 1979).

If a sample of grain at a given moisture content is exposed to a small, fixed volume of air in a closed system, it takes up or releases moisture in order to change the absolute humidity of its surrounding air and so reach equilibrium. There are no substantial changes in the grain moisture content because of the large capacity of the grain to hold moisture compared with the capacity of the air. This defines the air equilibrium relative humidity for that moisture content. Expressed as a fraction, it is called the water activity of the product.

An adsorption isotherm is constructed by placing dried grain into an atmosphere of higher relative humidity than the product equilibrium relative humidity, and raising the air humidity in successive stages until saturation is reached, which takes about seven days according to Pixton and Warburton (1968), observing the product moisture content at each stage. Similarly, a desorption isotherm is obtained by successive reductions in relâtive humidity from saturation. The resulting curves display the characteristic sigmoid shape (Fig. 1). The adsorption isotherm gives a higher equilibrium relative humidity for a given moisture content than a desorption isotherm. The area enclosed between the two curves is related to structural changes occurring in the surface of the grain, as the moisture condensing on the surface does work on the grain structure, opening up additional polar sites for condensation in subsequent cycles (Chung and Pfost 1967; Treybal 1981). This effect is called hysteresis. Repeated cycling between wet and dry conditions reduces

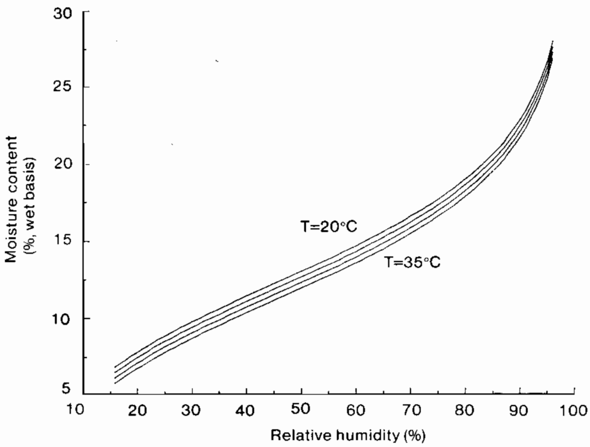

Fig. 1. Isothermal plots for rice variety Inga (from Putranon et al. 1979).

the hysteresis effect until, after a few cycles, it disappears completely (Chung and Pfost, 1967). However, the structural changes reduce the milling yield of the grain (Kunze and Choudhury 1972; J. Darby, pers. comm. ; Chung et al. 1984), so cycling is preferably avoided. The hysteresis effect means that the history of the grain since harvesting is significant in terms of the thermophysical and milling behaviour of the grain.

The effect of temperature on the air/grain equilibrium can be demonstrated by plotting several isotherms on the same plot. As the air temperature increases, the equilibrium relative humidity increases for a given grain moisture content. However, over a large range, the effect of temperature is small for all grains.

There are three important forms of equilibrium between a grain and its environment, and within the grain itself. The first is thermal equilibrium. It takes from about four minutes for the kernel centre to reach ambient temperature after a sudden change (Brooker et al. 1974, p. 189). The time required for moisture equilibrium varies from hours to days, or even weeks, depending on factors such as the grain type, whether the grain is husked or not, and temperature (Hsu 1984; Steffe and Singh 1979). Stress relaxation is the slowest form of equilibrium, taking over a month for grain subjected to a high vapour pressure drying gradient. A direct consequence of this factor is that, for experimental work, grains which require milling should be left for a month before milling in order to ensure repeatability of the experiments (Blakeney 1976; Chesterfield and Abbott 1974), and for commercial operations, tempering the stresses for a month ensures the maximum milling yield. For present purposes, temperature equilibrium can be assumed, since the time required for temperature equilibrium is small compared with the time required for drying. Stress equilibrium can safely be ignored, since it has no direct relationship with the grain/air interaction of stored grain. Thus, only moisture equilibrium is of direct concern in drying studies, and in many cases at sufficiently low airspeeds, even moisture equilibrium can be assumed during drying, as done by Sutherland et al. (1971), Bloome and Shove (1971), and many others.

An alternative way of plotting air/grain equilibrium data is to plot the data on psychrometric charts as lines of constant moisture content or isosteres, as in Figure 2. Such plots demonstrate that over substantial changes in temperature, lines of constant moisture content follow the lines of constant relative humidity, a reflection of the small effect temperature has on the water activity level in a grain. For example, for rice, a 10 degree change in temperature corresponds to a 2% change in relative humidity at a moisture content of about 16% wet basis. As the moisture content decreases, the effect of temperature becomes more significant.

The grain when harvested is initially not at a uniform moisture content, due to variations in position of the panicles, received sunlight, and maturity (Chau and Kunze 1982). However, except for loss of milling quality due to rewetting of the driest grains by moisture redistribution from wetter grains, this has no practical effect, the grains behaving as if the whole mass were at the

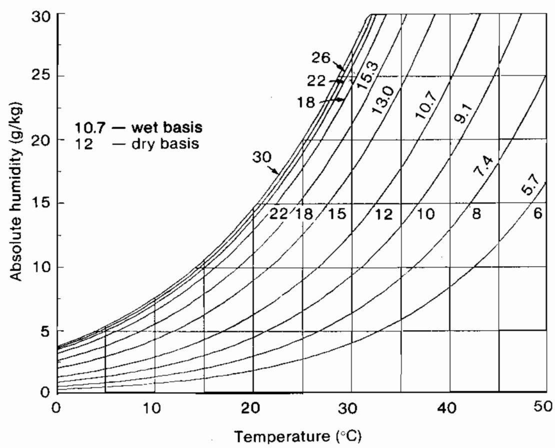

Fig. 2. Psychrometric plot of lines of constant moisture content for rice (from Putranon et al. 1979).

average moisture content. Thus, the isothermal data allow prediction of the drying behaviour of the grain mass. Berry and Dickerson (1973) presented isothermal data for a selection of different grains, including oats, corn, and soybeans. Over the past 20 years, large numbers of researchers have obtained detailed isothermal data for many different cereals (see, e.g., Zuritz et al, 1979; Putranon et al. 1979; Chung et al. 1984).

Drying Zones and Air Properties

As for the isothermal data for a particular grain, there is a substantial literature on the drying rates of grain. Early literature (and occasional later papers) assumed that the application of thin-film drying equations was valid [see literature survey in Dung (1980)]. Becker and Sallans (1955) and Becker (1959) showed that diffusion theory could be used to describe moisture movement within the grain, a result confirmed by many subsequent researchers, including Hustrulid and Flikke (1959) for corn, Hukill and Schmidt (1960) for exposed sorghum kernels (they showed that the thin-film model could not be applied), Henderson and Pabis (1961), van Rest and Isaacs (1968) for shelled corn, theoretical studies by Whitaker et al. (1969), Husain et al. (1973), and Hosokawa and Motohashi (1973), tempering studies based on diffusion theory by Steffe and Singh (1979), a combination semi-empirical/diffusion/thin-film model by Dung et al. (1980), Bakshi and Singh (1980) for parboiled rice, and Aguerre et al. (1982) for rough rice. Sharma et al. (1982) showed that a two-compartment model was necessary for accurate drying rate prediction. Suarez et al. (1982) studied the application of different elemental geometries to diffusion analysis of soybeans, rough rice, wheat, and peanuts. Steffe and Singh (e.g. Steffe and Singh 1980, 1982) have done considerable research into diffusion drying behaviour for grains.

A wet, hygroscopic solid exposed to a steady-state drying regime dries in two distinct stages, separated by transitional periods (Treybal 1981). The stages are the constant drying rate period and the falling rate period. The fine detail of the mechanisms of moisture movement within the grain are not within the province of the current topic, but the two stages are briefly outlined as necessary background to the role of drying rates in air/grain interaction.

The first stage involves the removal of unbound moisture, that is, all moisture contained in the product above the critical moisture content (Treybal 1981). The critical moisture content, which is temperature dependent, is defined as the minimum moisture content at which the solid exerts a vapour pressure equal to the saturation partial pressure of the ambient air, so that the equilibrium relative humidity of the product is 100%. However, for grains, the drying rate is observed to be constant until the equilibrium relative humidity drops below about 75% (Brooker et al. 1974, chapter 8). During this stage of drying, moisture is removed at a constant rate from the solid, due to the steady state balance which arises between removal of heat from the solid by evaporation of moisture and the convective transferral of heat from the air to the solid. Provided the air flow is sufficient to remove the evaporated moisture, the product temperature drops during the initial transient period to the air wet bulb temperature and stays at that temperature throughout the constant drying rate period, an effect observed in grain by many researchers well before grain-drying theories were very advanced (Boyce 1966; Person et al. 1966; Cromarty 1964). The minimum critical air speed depends on factors such as the air humidity and temperature, but is an order of magnitude less than air speeds used in slow dryers.

As the moisture on or near the surface is removed, dry spots start appearing on the grain and the rate of evaporation starts to decrease. Successive new balance points are reached between the rate of heat loss through vaporisation of moisture and the rate of heat transfer from the air, so the product temperature rises accordingly. After a transitional time of variable length, a second stage called the falling rate period begins and continues for the remainder of the drying process. The rate of moisture removal is increasingly controlled by the rate of moisture diffusion through the grain, either by vapour or liquid diffusion. The rate of diffusion in turn is governed by the structure of the product, the internal temperature, and the moisture gradients within the product.

The whole drying process can be plotted on a psychrometric chart of temperature against absolute humidity, as in Figure 3. The condition of the grain is plotted on the chart by its dry bulb temperature and equilibrium moisture content. The initial transition stage to the constant rate

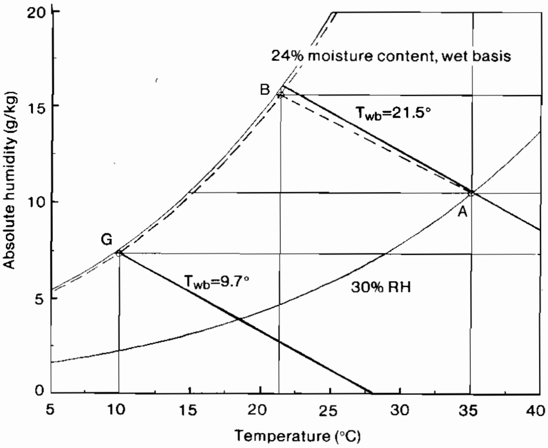

Fig. 3. Psychrometric representation of grain drying. A, inlet air conditions; B, intermediate grain state; G, initial grain conditions.

period consists of an enthalpy equilibrium being established between the grain and the air. On the psychrometric chart, the grain moves from its initial temperature and equilibrium relative humidity along a line of approximately constant moisture content until its temperature matches the wet bulb temperature of the air. If sufficient moisture is present, the grain moves along the 100% humidity line. The remainder of the drying process for steady state conditions is an adiabatic process and can be approximately represented on the chart by constructing the wet bulb temperature line from the inlet air point to its intercept with the 100% humidity line. The product stays at the intercept point during the constant rate period, and moves towards the air point during the subsequent transitional stage and final falling rate period. The state of the grain at any point can thus be conveniently represented by its temperature and its equilibrium relative humidity.

From the preceding discussion for a thin layer of grain, above a certain critical air speed which is the minimum sufficient to remove the evaporated moisture from the immediate vicinity of the product, no part of the drying curve is affected by the air speed, apart from minimal changes in the air/product heat transfer coefficient (Treybal 1981, p. 675–676; Henderson and Pabis 1962). For grains, field drying is generally practiced, so that the harvested moisture content is generally less than the critical moisture content, and the product possesses only bound moisture. For example, for rice the average harvest moisture content in Thailand is about 21% wet basis, well below the critical moisture content of about 30% wet basis. Acute problems occur in wet season harvests when this is not true.

Deep Beds of Grain

For a thin layer during the falling rate period, the humidity of the exit air decreases as the product dries, so that the effective utilisation of the air passing through the grain decreases. Consequently, there are significant advantages both in handling and in air economy in drying deep beds of grain (Thompson et al. 1968), since the exit air from one layer passes into the next layer, adsorbing more moisture as it moves through the bed.

Thus, for a deep bed product, the situation is more complicated than for thin-layer drying. For an initially uniform bed subject to uniform air inlet conditions, the air will remove moisture first from the grain nearest the inlet, called the inlet layer. As the inlet layer dries and the air passing out of it drops in relative humidity, more moisture will be picked up from the second layer. This is the conceptual basis of Thompson's model of grain drying. Theoretical modelling results indicate that, for constant inlet conditions, a drying front is

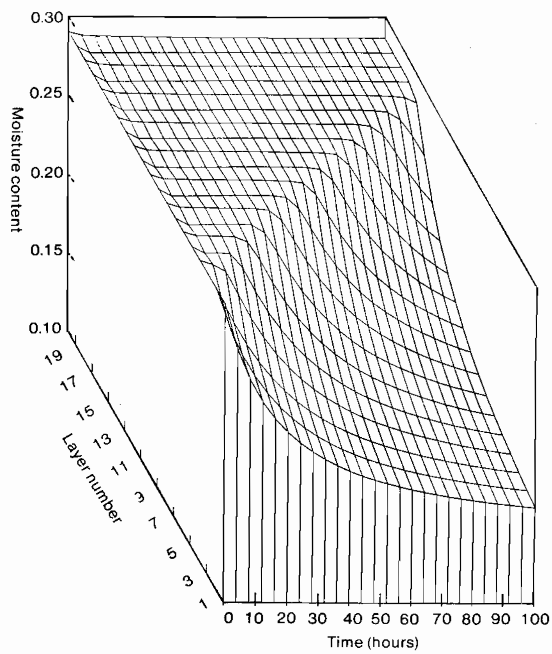

Fig. 4. Representation of deep-bed drying under constant inlet conditions: a plot of time versus layer number versus moisture content.

formed which moves slowly through the bed, the width of the front depending on the air speed and the difference between the initial bed equilibrium relative humidity and the inlet air relative humidity (Barre et al. 1971). Until the drying front leaves the deep bed, the exit air leaves at the humidity of the exit layer grain, so that the air passing through a deep bed is utilised in the most effective way, as shown by Figure 4. This diagram is a three-dimensional plot of time versus layer number versus moisture content, showing the complete moisture profile history of a grain mass during drying, as predicted by a near-equilibrium model. There are three main zones depicted in the diagram: the initially high moisture grain (the plateau in the top left of the diagram); the drying front (the scalloped zone); and the dried grain (seen as a new plateau area forming in the bottom right of the diagram). Slight evidence of the temperature front moving through the grain mass very quickly can be seen in the difference between the bed profiles at time zero and 4 hours after start of drying. Figure 5 shows the same drying situation, but from the point of view of the temperature profile as a function of time. The temperature front is dramatically evident in this plot.

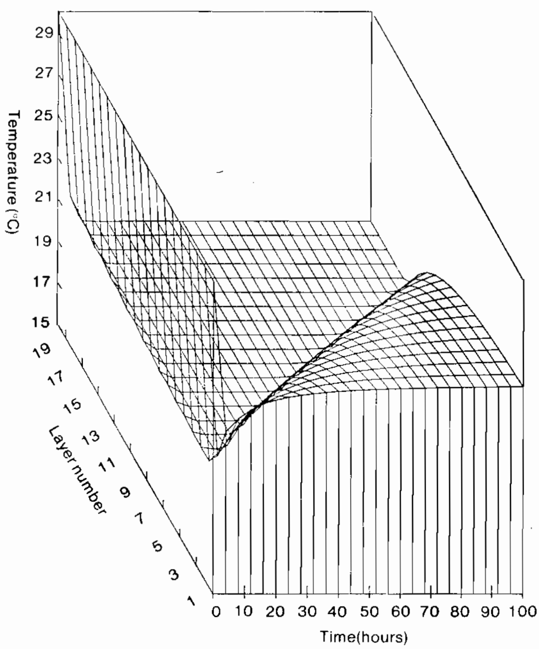

Fig. 5. Representation of deep-bed drying under constant inlet conditions: a plot of time versus layer versus temperature.

In contrast to thin-layer drying, air speed now becomes crucial. At slow airflow rates the air economy is highest and the pressure drop across the bed is least, the fans doing less work to force the same quantity of air through the grain, whereas at high flow rates, the drying front broadens as the rate of diffusion of moisture within the grains becomes predominant, so that the air is not given sufficient time to remove the moisture as it moves through the bed. Further, the pressure drop across the bed increases more quickly than the air speed. At low airflow rates the pressure drop is linear with speed, but at higher air speeds, a quadratic term becomes dominant (Bird et al. 1962; Teter 1982; University of New South Wales, Sydney, unpublished data).

Consequently, careful consideration must be given to designing a grain drying system, in order to locate the optimum balance between removing the moisture quickly for quality reasons, and using slow flow rates for energy conservation.

As with single layer drying, the deep bed drying process can be represented on a psychrometric chart. This first became possible around 1971 with the development of the equilibrium model of Sutherland et al. (1971), applied to wheat in Australia. It was found that, at low flow rates, the simultaneous heat and mass transfer operations occurring in a deep bed of biological products could be conveniently represented by wave theory developed by Aris and Amundsen (1973) and applied by Banks (1972). Assuming equilibrium at every point in the bed between the air and the grain temperature and moisture content, the drying process is summarised by a mass conservation and an enthalpy conservation equation, the solution of which consisted of two waves which pass through the bed, an enthalpy wave (or 'front'), and a moisture wave. The enthalpy wave normally passes through the bed at about 30 to 60 times the speed of the moisture front, the main effect on the grain being a change in its temperature. The moisture front was a change in grain moisture content which occurs at constant enthalpy. Thus, if the assumption of equilibrium is valid, the drying of a deep bed under constant conditions can be conveniently represented by a curve from the initial grain condition point along the constant moisture content line, and the wet bulb temperature line through the initial air point. The two curves intersect at a point called the B zone (the inlet air being the A zone and the initial grain state

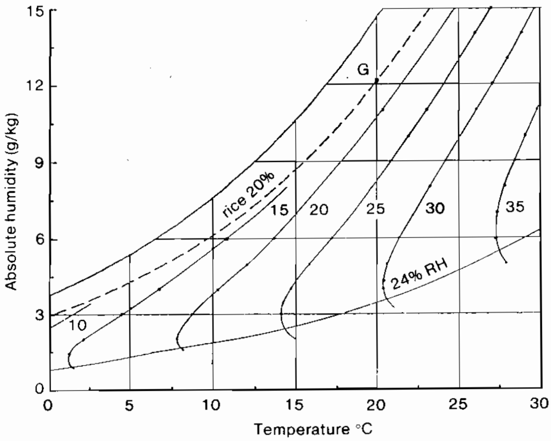

Fig. 6 Psychrometric plot of lines of constant moisture front speeds for rice at 20% moisture content (dry basis).

being the C zone). The above method is only an approximation even if the equilibrium assumption is valid, since in practice small changes in moisture content (up to 1 or 2%) do occur over the enthalpy front and, conversely, small changes in enthalpy occur over the moisture front. However, for conceptual convenience, the above is sufficiently accurate. The above method of representation can be extended to non-equilibrium situations, provided it is clear that a single point on the drying curve no longer represents both the air and the grain state at a single point in the grain bed. In the non-equilibrium case, for a given grain point, the air point will be further along the curve towards the inlet air conditions.

Figure 6 is an example of a type of graph which can be used for estimating front speeds. On a psychrometric chart, the isostere for rice at 20% moisture content (dry basis) has been superimposed. The curves labelled 10, 15, 20, 25, 30, and 35 correspond to speeds of moisture fronts if the inlet conditions were on that curve. To obtain the actual speed of the moisture front in m/hour, multiply the number on the curve by the superficial air speed and divide by 104. For example, for rice at 20% moisture content (dry basis) being dried by air at 58% relative humidity (RH) and 20°C, with an airflow rate of 5 m/minute, the moisture front moves at speed:

$$\text{speed} = 25 \text{ (from graph)} \times 5\text{(m/minute)}/104$$

giving 0.0125 m/min or 0.75 m/hour. The graph is valid only for rice at 20% moisture content (dry basis) and under equilibrium conditions. A more general approach to estimating air speeds is described by Bowrey and Driscoll (the proceedings).

The method is also not valid when the process is not adiabatic. Non-adiabatic influences include any additional source of heat (respiration, sun, heating coils) or loss of heat (through bin walls). In the majority of situations these effects can be neglected.

Probably the single most important consequence of the growth of grain drying theory has been in the ability to predict what happens when the ambient conditions fluctuate. Figure 7 shows a drying front entering a grain bed, and conditions being held constant for 2 days. After 2 days, the dry air is replaced by air at a higher relative humidity, causing a 'wetting front' to enter the grain. The wetting front broadens as it enters the grain, so that after 10 days it has caught up with the drying front. The two fronts effectively combine, producing a single weaker drying front. Work by Sutherland et al. (1983) confirms that fronts tend to be additive in effect. This can be most clearly seen in Figure 8. A rice bed initially contains a mixture of rice at different moisture contents, as shown by the bed profile at time 0. Fluctuating ambient conditions

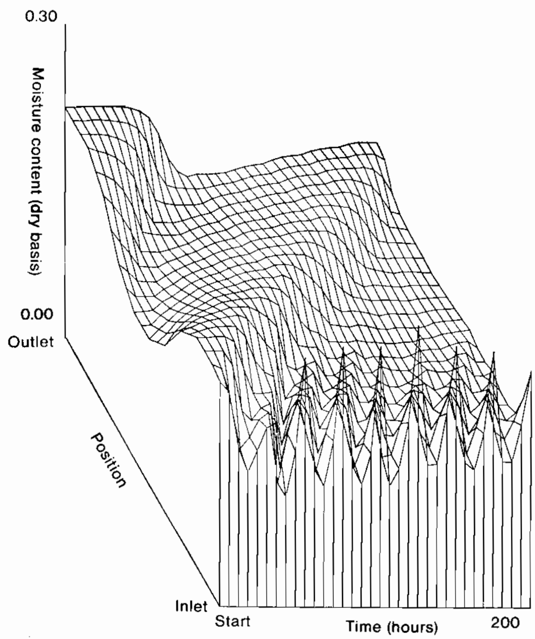

Fig. 7. Moisture content profile of a deep-bed of grain for a non-uniform initial bed state and varying inlet conditions.

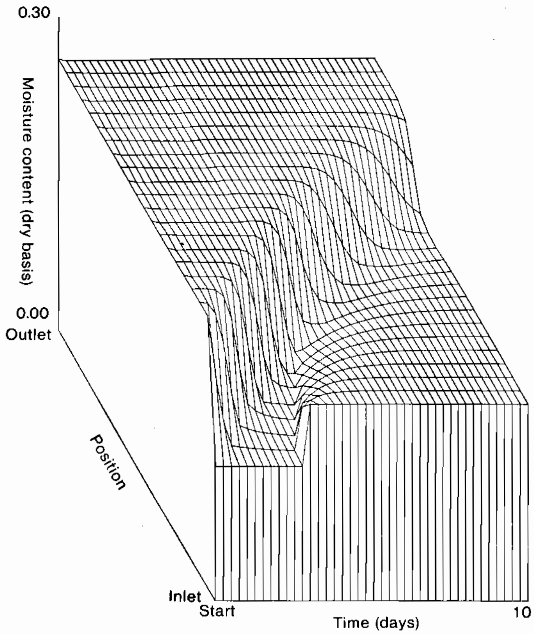

Fig. 8. Moisture content profile of a deep bed of grain showing an interacting drying and wetting front.

are then fed into the bed, the inlet conditions being reflected by the sharp peaks at the inlet of the bed. Despite the rapid fluctuations, the oscillations dampen down within a few layers of the inlet, producing comparatively uniform grain conditions. This point will be returned to later.

Aeration Storage

Once the grain is dried, it must still be aerated occasionally in order to prevent the development of off odours, of hot spots caused by local insect activity, of wet spots caused by circulation currents from hot to cold areas, and of moisture migration caused by contact with atmospheric conditions of different humidity. The air must be chosen according to the climatic conditions. In temperate climates the preferred air may be early morning air. This has a low temperature, which increases the grain storage life (Hukill 1953) and high humidity, which counters the hot, dry summer days that 'suck' the moisture out of the grain, leaving it over-dried). In tropical climates the preferred air may be early evening air, when the air is cooling but still at a lower relative humidity. Ideally for very moist climates, the aeration air should be both cool and dry, and this suggests some dehumidifying system for bulk grain aeration.

Teter (1982) brought together ideas from several different sources, about designing grain storage aeration systems for humid tropical countries. He discussed how the quality parameter called dry matter loss (DML) and the air parameter called the deterioration index could be used to estimate the minimum aeration requirements for grain storage. DML has proven to be a useful quality parameter despite its known limitations and has come to be widely accepted throughout Southeast Asia and the United States. The work by Seib et al. (1980) in developing the DML parameter has resulted in a convenient equation expressing it as a function of temperature, time, and moisture content, allowing simulation studies to estimate the final quality change due to a given drying strategy. Figure 9 is a plot of the value of the DML as a function of time and position in the grain bed for the drying situation discussed in the previous section (see Figs 7 and 8). Once the grain has been dried, the DML parameter changes very slowly, so that grain near the inlet shows a much lower value for DML than grain near the exit, which takes longer to dry.

The deterioration index is a concept developed by Brooks (Mackay and Jamieson 1970), relating

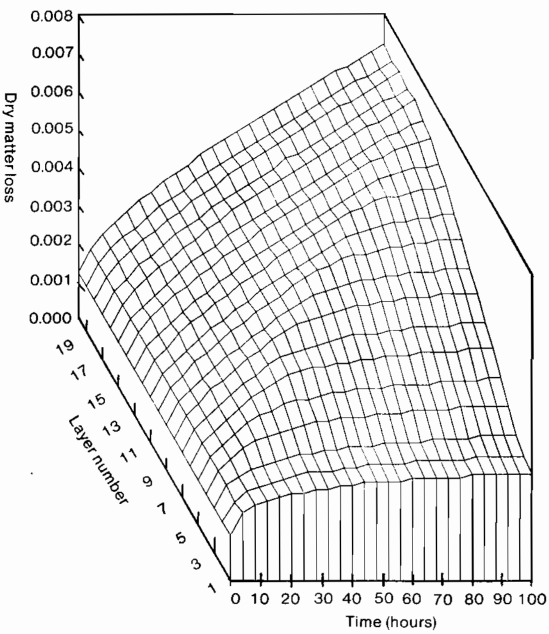

Fig. 9. Dry matter loss profile of a deep-bed of grain as a function of time and position during drying.

the weather conditions to the rate of growth of microorganisms and the rate of grain consumption by insects and rodents. It is defined in a similar way to the partial pressure of water vapour in the air, but only the partial pressure component above 65% RH is included in the definition:

$$DI = (\%RH - 65) \times P_{as} \times 10^{-4}$$

where DI is the deterioration index, %RH is the percent relative humidity, and P_{as} is the saturation partial pressure of water vapour expressed in Pascals. For average tropical conditions, the DI varies from 0 to 10. Teter (1982) examined DI values for 13 cities in the Philippines, taking the average monthly climatic conditions. For DIs below a certain critical value that depends only on the grain type, a particular grain can be stored indefinitely, provided that it has been suitably dried. Above the critical DI value, the grain must be aerated or stored in a modified environment.

At present, a few researchers are studying circulation currents in bulk stored grain.

Daily Weather Variation and the Wet Season

With the assistance of the Australian Department of Science and Technology and the governments of several Southeast Asian countries, extensive weather records have been collected at the University of New South Wales, Australia as part of a collaborative research project on grain drying funded by ACIAR (Mochtar et al. 1985).

Several researchers have attempted to derive mathematical formulae which would allow predictions of weather data based on knowledge of global air movements. Ward and Shapiro (1961) used a power series containing over 2000 terms, coming to the conclusion that only diurnal and annual variation was significant in the observed atmospheric oscillations of air masses. Some research has indicated that recent trends (over the past decade) are significant in predicting annual behaviour, but in general weather prediction remains uncertain and difficult to analyse. Most models are quasi-empirical (Glahn 1965). One of the most successful methods has been the Model Output Statistics method (MOS), in which a statistical relationship is determined between the predicted variable and variable determined to be weather-related, using multiple linear regression (Glahn and Lowry 1972). Most weather models are extremely complex (Balgovind et al. 1983; Yao 1983) and beyond the realms of easy application. In consequence, only diurnal and annual variations will be considered.

Figures 10 to 12 are diurnal plots of temperature and RH patterns for Kuala Lumpur, Bangkok, and Kota Bharu. The plots show the typical diurnal variation of high night RHs but strong solar dependent dips in RH during the day, even during the wet season. Figure 12 shows, in addition to temperature and RH data, diurnal profiles of absolute humidity, and indicates the general stability of absolute humidity. The direct consequence of this is that a temperature control or an RH control will both lead to a constant inlet RH, the most gentle way of drying grain. A temperature control system is an air-conditioning system which modifies the inlet air temperature in order to obtain a constant outlet temperature. An RH control system is one which modifies the inlet air temperature in order to obtain a constant RH.

Note that plots of RH and temperature versus time of day show very little evidence of the effect of the wet season, although it would be expected that higher RHs would be apparent. Furthermore, the monsoon or wet season varies greatly in character from one place to another. In one area it may involve continual rain accompanied by thunderstorms, in another intermittent rain with afternoon downpours but no storms, and so on. In many areas the wet season is not a major effect on the ambient air humidity. At Subang, Malaysia, for example, there are periods during the day when the ambient humidity drops to 60%, but as soon as the sun sets, RH climbs to 100% for the night, all year round.

Thus, for many areas, the RH is closely tied to the time of day. This is a useful factor for near-ambient drying, but the grain must be sheltered from the direct effects of the atmosphere for the wet season, so that sun drying is not possible.

Drying Strategies

There are many factors involved in choosing what air is used in drying grain at near-ambient conditions. The air itself can be described by five main parameters, and how these five variables are chosen constitutes the selection of an air-drying strategy. The five variables are the inlet temperature, inlet RH, time of day at which air is used, air speed used (conventionally expressed in terms of cubic metres of air per tonne of grain per minute), and amount of supplementary heat added (both by

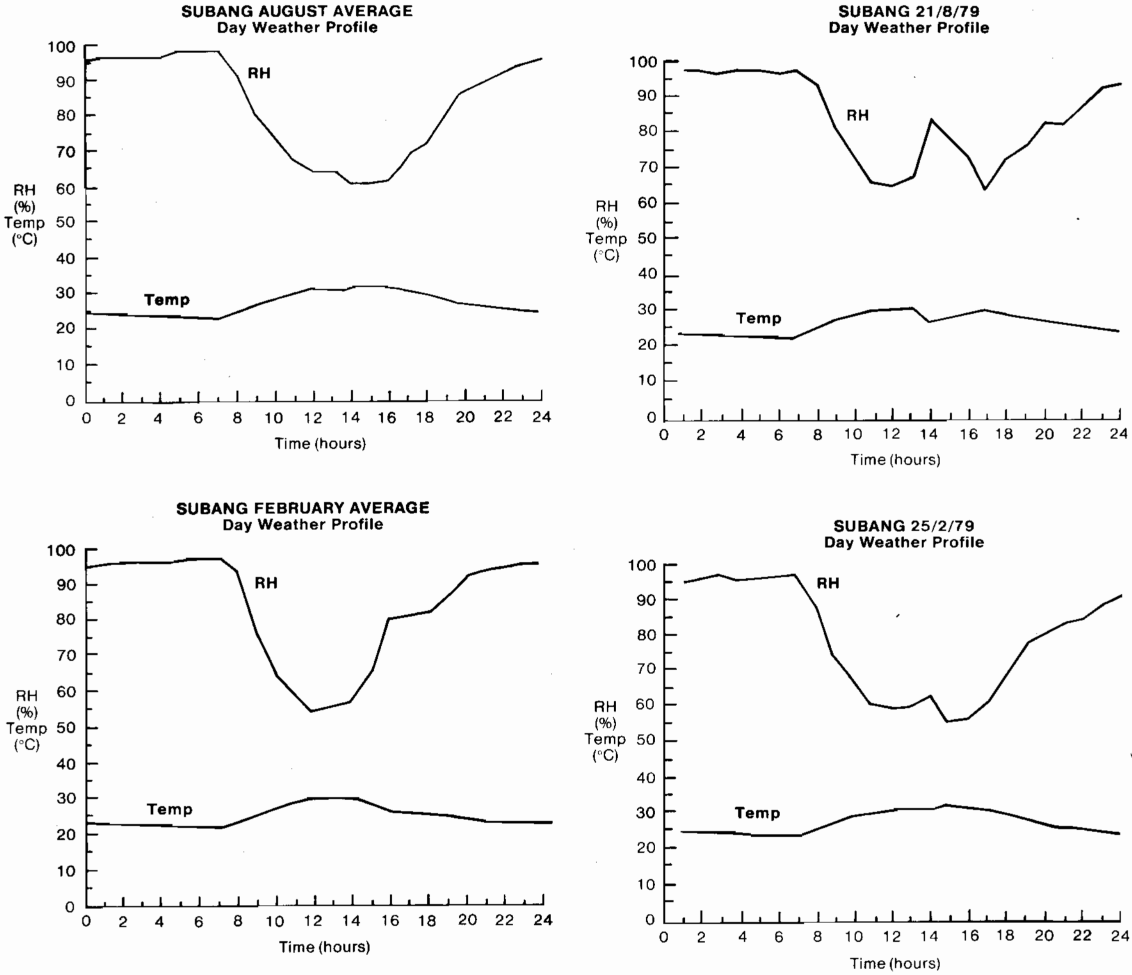

Fig. 10. Diurnal weather plots for Subang, Malaysia.

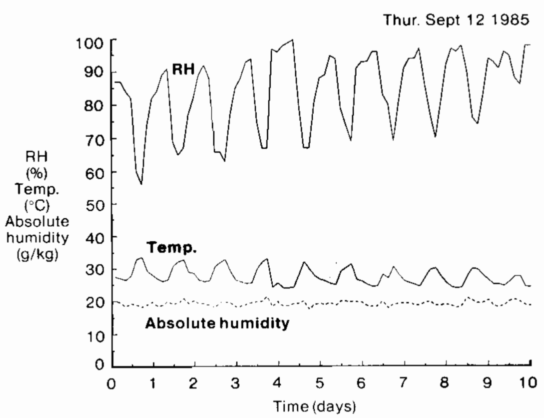

Fig. 11. Plots of absolute humidity, temperature, and relative humidity over a 10 day period for Bangkok, Thailand.

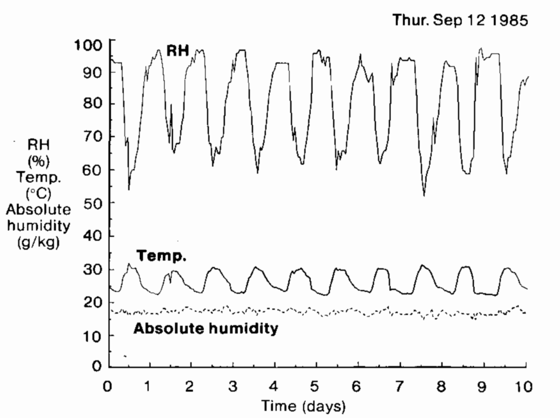

Fig. 12. Plots of absolute humidity, temperature, and relative humidity over a 10 day period for Kota Bahru, Malaysia.

the fan and by a mechanical heat source such as a burner). A complete drying strategy must include consideration of factors such as the grain bin dimensions and the receival moisture of the grain in addition to the air variables. In practice, there are additional constraints generated by the different costs of different heating methods, the level of trash present in the grain, the history of the grain since harvesting, the availability of different energy sources, and the urgency of keeping the mill or packaging facilities supplied with dried grain.

If ambient air is passed continuously through a deep bed, the cyclic conditions described in the previous section mean that there are times when low RH air is entering the bed (during the heat of the day), and times when the inlet air is saturated. Thus, the bottom layer will cycle in moisture content with the air conditions, drying and rewetting.

Consider firstly the period of the day when the grain is drying. A drying front will be formed, starting at the inlet and propagating into the grain mass as it removes moisture from the first few layers. After a few hours, the inlet layer will have lost sufficient moisture to be in equilibrium with the ambient conditions. As evening advances, the ambient temperature drops and the RH rises as a result, so that the air entering the grain mass is at a higher RH than the equilibrium RH of the grain. The grain will pick up moisture from the air, and a wetting front will be initiated and start propagating through the bed. There are now two fronts, a drying and a wetting front. Theoretical work by Sutherland et al. (1983) proved that fronts tend to interact (see discussion of deep-bed drying and Figs 7 and 8). The wetting front will broaden in such a way that it catches up with the drying front and interacts with it, the two fronts tending to cancel each other out, or more precisely, to add together forming one front which behaves like the average of the drying and wetting fronts.

When the many small wetting and drying fronts that are initiated during the day are added together, it becomes clear from theoretical simulation work that a grain mass possesses a high degree of inertia with respect to changes in weather conditions. The first layer of a bed will tend to cycle with the ambient weather conditions, but subsequent layers are increasingly governed by the average inlet conditions. An adequate model for most drying situations is simply to look at the average inlet air conditions, and estimate the grain bed's response on the basis of these conditions.

As a result of this fact, the most important air parameter in ambient air drying is the average RH of the inlet air. In analysing a deep bed, the grain at the outlet of the bed will be of lowest quality, because it is the last to lose its moisture. In many practical situations, it is of more benefit to remove some moisture from all of the grain quickly in order to maximise the final grain quality, by pushing a weak drying front through the bed as fast as possible. A weak drying front is achieved by using all of the available air, and is the fastest way to affect the moisture content of the top layer of the grain. Conversely, if quality is less crucial, air may be chosen which satisfies certain RH requirements. A stronger drying front will be formed, which on average moves a shorter distance per day through the grain mass than the weaker, fast front.

Examples of the applications of strategies are shown in Figure 13. Ambient 1982 air from Wagga Wagga, New South Wales, Australia was used as the input to a grain-drying simulation program, the average moisture content of the bed being monitored. Three RH based strategies were implemented. The first was to allow all of the air to pass through the grain. The first six weeks of the grain-drying history shows consistent drying. As winter approached (mid-May), the average ambient RH started to rise, so that the grain was rewetted over winter. Then in summer (September on), the grain was overdried by the hot, dry summer air. Clearly, using all ambient air is not a good strategy. The grain is rewetted, the fan costs are high, and the final product is over-dry.

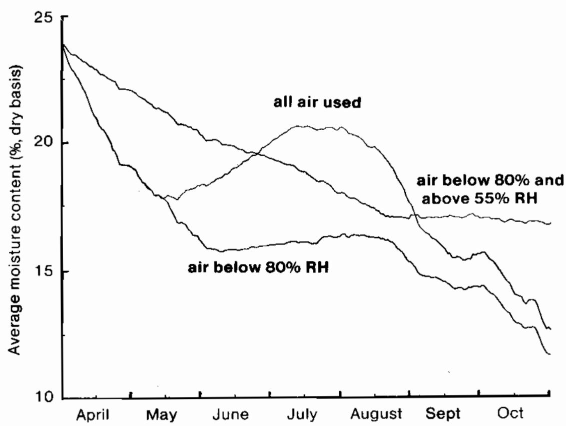

Fig. 13. Comparison of various relative humidity strategies for drying grain using ambient air; date versus average moisture content.

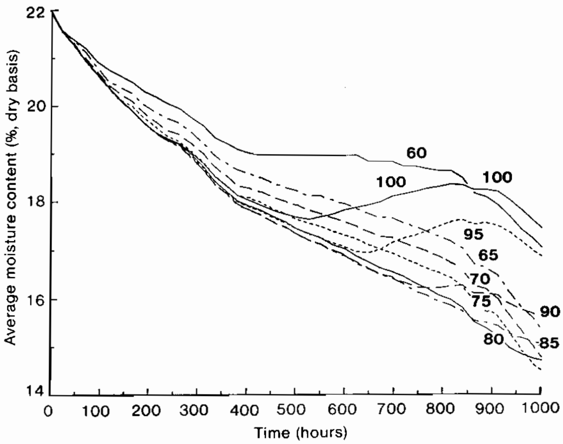

Fig. 14. Comparison of various relative humidity strategies for drying grain using ambient air at Bangkok; date versus average moisture content.

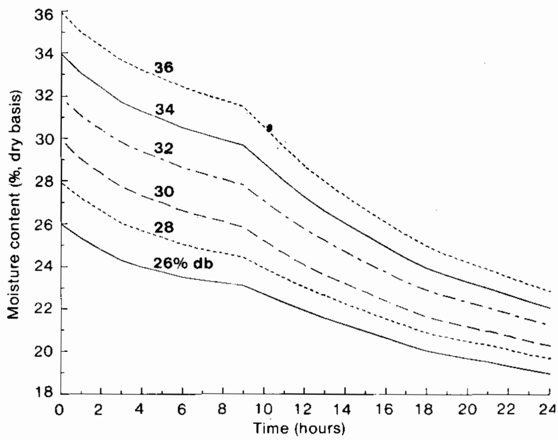

Fig. 15. Effect of intial moisture content for flat-bed, high-speed grain drying; time versus bed average moisture content, Bangkok.

The second strategy was to choose only air below 80% RH, in order to avoid the resetting problem of winter. The method works well until the end of May, and even over winter only slight rewetting occurs. However, the drying problem is exacerbated for summer. Again the strategy is not good.

The third strategy involved choosing air below 80% but over 55% RH, in order to avoid overdrying. Clearly this produced a final high quality grain in terms of moisture control. However, the time required to dry the grain sufficiently for milling is more than doubled, so a higher risk of grain deterioration exists. Again this is not an effective strategy. However, combinations of the above strategies suggest use of air below 80% RH until the end of May, and only occasional aeration after then.

Figure 14 relates to a two week period in Bangkok. Grain is being dried from 22% moisture content (dry basis) using ambient air. Each drying line corresponds to an RH strategy. Only air below the restriction RH was allowed to enter the grain. Clearly there is an optimum RH around 80%: above it, too much wet air enters the grain; below it, insufficient air enters the grain to dry it quickly.

Figure 15 shows the results of fast-drying simulations of grain in Thailand, where the initial grain moisture content is varied. Clearly, the receival moisture content of the grain is critical in designing a drying system which will dry the grain quickly enough to avoid quality losses.

Many other aspects of drying strategies could be investigated, including flow rates, the effects on quality of different strategies (using the dry matter loss parameter), and the implications of grain bed dimensions as, for example, were demonstrated by Bridges et al. (1980) for layer filling of bins.

Conclusions

This paper has attempted to describe current understanding of grain drying from a viewpoint of grain properties. Research tools important to this type of study have been outlined, and methods of approach to drying situations discussed.

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Modelling Temperature and Moisture Changes Resulting from Natural Convection in Grain Stores

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Abstract

Moisture migration is a result of air convection currents which increase in relative humidity and transfer moisture to the grain as they pass through cooler regions in the grain store. As moisture accumulates in these regions, the grain becomes first caked and finally a moulded, decomposed mass. The accumulation of moisture also makes conditions more favourable for pest infestation.

A numerical analysis which describes the moisture migration by natural convection in stored cereal grains, under fluctuating thermal boundary conditions, was performed. The two-dimensional, transient equations, assuming local thermal and thermodynamic equilibrium, have been solved by powerful numerical methods. Results have been obtained for a rectangular bin and a bunker-type storage. They should describe the actual course of moisture migration and the temperature distributions in such structures.

COMBINED heat and mass transfer in a porous medium is a process which occurs frequently in nature as well as in various engineering endeavours. Drying and humidification in chemical processes and climate control, and movement of moisture in stored cereal grain are examples. Such processes have therefore been widely studied by scientists and engineers over many decades.

Moisture migration resulting from convection currents has been a major problem in grain storage technology, especially as regards storage in plastic enclosures, a technique which is increasing in popularity. The movement of moisture resulting from natural convection gives rise to many problems. These include accelerated development of pest infestation, mould growth, mycotoxin formation, and deterioration in quality. Under some circumstances, convection currents can be useful: for example, they promote the even distribution of fumigants through a grain bulk.

Though heat and mass transfer in porous media has received a great amount of attention recently, there has been relatively little work done on the transient character of moisture migration by natural convection in cereal grain storage. An analysis of heat and moisture transfer processes is complicated by many factors. The structure of the solid matrix varies widely in shape. It may, for instance, be composed of cells, fibres, or grains. Energy transport in such a medium occurs by conduction in both solid and fluid as well as by convection within the fluid. Mass transport occurs within the voids of the medium. The processes of heat and mass transfer are coupled, since heat is transferred as the porous medium releases or absorbs moisture. Also, the equilibrium concentration of the moisture in the medium depends on its temperature.

A detailed study of the transport processes occurring within the solid matrix and in the voids is very complicated even for a regularly shaped matrix and is impossible for the irregular void configurations which, in general, characterise porous media. The normal approach in an analysis is therefore to consider the media involved as continua. The energy and mass fluxes are then a consequence of constitutive equations which include various driving forces.

The present paper uses this approach to study the movement of moisture by natural convection in grain storages of different geometries and boundary conditions.

Numerical Model

Consider a grain bulk of permeability κ and porosity ε which is subject to a temperature

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gradient ΔT and pressure P. The air has thermal expansion coefficient β, density ρ, and dynamic viscosity μ.

The linear law of motion due to Darcy can be written as

$$\frac{\rho}{\varepsilon}\frac{\partial \underset{\sim}{V}}{\partial t} = -\text{ grad p} + \rho \underset{\sim}{g} - \frac{\mu}{\kappa}\underset{\sim}{V} \quad (1)$$

where $\underset{\sim}{V}$ is the filtration velocity and $\underset{\sim}{g}$ is the gravitational acceleration.

Introducing Boussinesq's approximation which assumes that the variation of density with temperature is negligible except in the buoyancy term of the equation of motion, and a vorticity ζ defined by $\zeta = \partial v/\partial x - \partial u/\partial y$, where u and v are the x and y components, respectively, of $\underset{\sim}{V}$, equation (1) becomes

$$\frac{\rho}{\varepsilon}\frac{\partial \zeta}{\partial t} = -\beta g \rho \frac{\partial T}{\partial x} - \frac{\mu}{\kappa}\zeta \quad (2)$$

The water and energy conservation equations for continuous changes are adapted from the basic analysis given by Banks (1972), taking into account the heat of respiration

$$\varepsilon \frac{\partial w}{\partial t} + \gamma \frac{\partial W}{\partial t} + u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} = 0 \quad (3)$$

$$\gamma \frac{\partial H}{\partial t} + u\frac{\partial h}{\partial x} + v\frac{\partial h}{\partial y} - \frac{k^*}{\rho}\nabla^2 T - \frac{R}{\rho} = 0 \quad (4)$$

where w and W are the moisture contents of air and grain, h and H are the enthalpies of moist air and moist grain, respectively, and R is the heat of respiration.

After some manipulation and substituting the properties of grain (see Sutherland et al. 1971), equation (4) can be written as

$$\frac{\partial T}{\partial t} = \frac{1}{c_m + c_w W}\Big\{-\frac{h_s}{\gamma}\Big(u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y}\Big) - \frac{1}{\gamma}\Big(c_a + c_w w + w\frac{\partial h_v}{\partial T}\Big)\Big(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}\Big) + \frac{k^*}{\rho\gamma}\nabla^2 T + R\Big\} \quad (5)$$

Equations (2), (3), and (5) can now be expressed in a non-dimensional form:

$$\frac{f_c}{Pr}\frac{\kappa}{\varepsilon L^2}\frac{\partial \zeta'}{\partial t'} = -\text{ Ra}\frac{\partial T'}{\partial x'} - \zeta' \quad (6)$$

$$\frac{\partial w}{\partial t'} + \gamma\frac{\partial W}{\partial t'} + u'\frac{\partial w}{\partial x'} + v'\frac{\partial w}{\partial y'} = 0 \quad (7)$$

$$\frac{\partial T'}{\partial t'} = \frac{c_a}{\gamma(c_m + c_a W)}\Big\{-\frac{h_s}{c_a\Delta T}\Big(u'\frac{\partial w}{\partial x'} + v'\frac{\partial w}{\partial y'}\Big) - \Big(1 + \frac{c_w}{c_a}w + \frac{w}{c_a}\frac{\partial h_v}{\partial T}\Big)\Big(u'\frac{\partial T'}{\partial x'} + v'\frac{\partial T'}{\partial y'}\Big) + \nabla^2 T' + \frac{H^2\rho}{\gamma\Delta T k^*}R\Big\} \quad (8)$$

with $x' = x/L$; $y' = y/L$; $u' = uL\rho c_a/k^*$; $v' = vL\rho c_a/k^*$; and $T' = (T - T_1)/\Delta T$

The following ratios of the latent heat of vaporisation of water in grain to that of free water are used in the present study

$$\frac{h_s}{h_v} = 1 + 23\exp(-40W) \quad \text{for wheat} \quad (9)$$

$$\frac{h_s}{h_v} = 1 + 2.566\exp(-20.176W) \quad \text{for paddy} \quad (10)$$

and the relationship between h_v and T,

$$h_v = 2502.39 - 2.3768T \quad (11)$$

Expressions for h_s and $\frac{\partial h_v}{\partial T}$ are obtained from equations (9), (10), and (11) and substituted into equation (8) to fully specify the problem.

The governing equations of motion, mass, and energy, together with the Poisson equation, were discretised by replacing the spatial derivatives with second-order central difference approximations and the time derivatives with forward difference approximations.

The resulting finite difference equations were then solved by the Samarskii-Andreyev Alternating Direction Implicit Scheme. A combined Fourier Analysis-Fast Fourier Transform direct method was used to solve the Poisson equation (Leonardi 1984).

Results and Discussion

The results presented here are for a rectangular storage bin of square cross-section and for a bunker-type storage. The temperature and moisture content of the grain are prescribed as initially uniform and the temperature of one or more surfaces varies with the ambient air temperature.

Figure 1 shows the results for a rectangular storage bin, one side heated by solar radiation and the top insulated. The initial grain temperature is 25°C and the temperature of the hot side is assumed to be 50°C during daytime and 25°C during nighttime. The temperature in the grain bulk changes slowly except for the layers next to the hot bin wall. From an initially uniform distribution, the temperatures at the centre and at the right wall remain the same after 12 months of

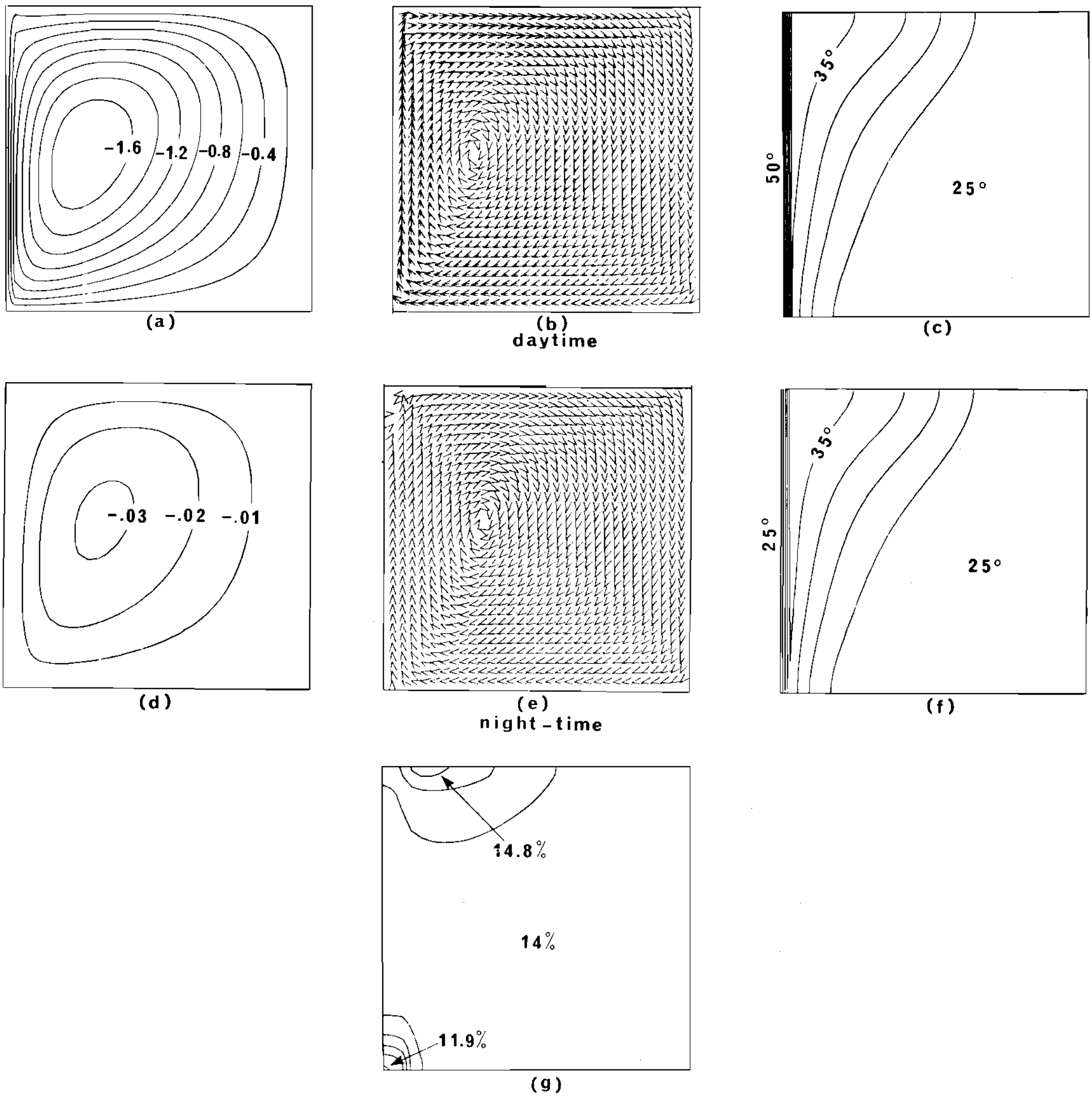

Fig. 1. Convective flow and temperature and moisture distribution in a rectangular grain bin with insulated top after 12 months of storage: (a,d) streamlines; (b,e) velocity vector plots, (c,f) isotherms; and (g) moisture distribution.

storage. The convection currents during daytime are quite strong, as shown in Figure 1(b) in which the lengths of the arrows represent the air velocity. The isotherms, lines of constant temperature, are distorted by these convection currents, resulting in a warmer region of grain near the top left corner. At nighttime, when large temperature gradients no longer exist, the air circulation is greatly reduced and conduction is the dominant heat transfer process near the wall. Figure 1(g) shows the distribution of moisture content in the grain store. Moisture migration is in this case a direct consequence of the convection currents. Moisture is transferred from the grain to the warm air which rises along the hot wall. It is then carried by the convection currents to the cooler region near the top left-hand corner and lost to the grain. Consequently, the moisture content increases in the region at the top of the bin and decreases in the region below.

When the top of the storage bin is not insulated but is exposed to sunshine, the airflow patterns

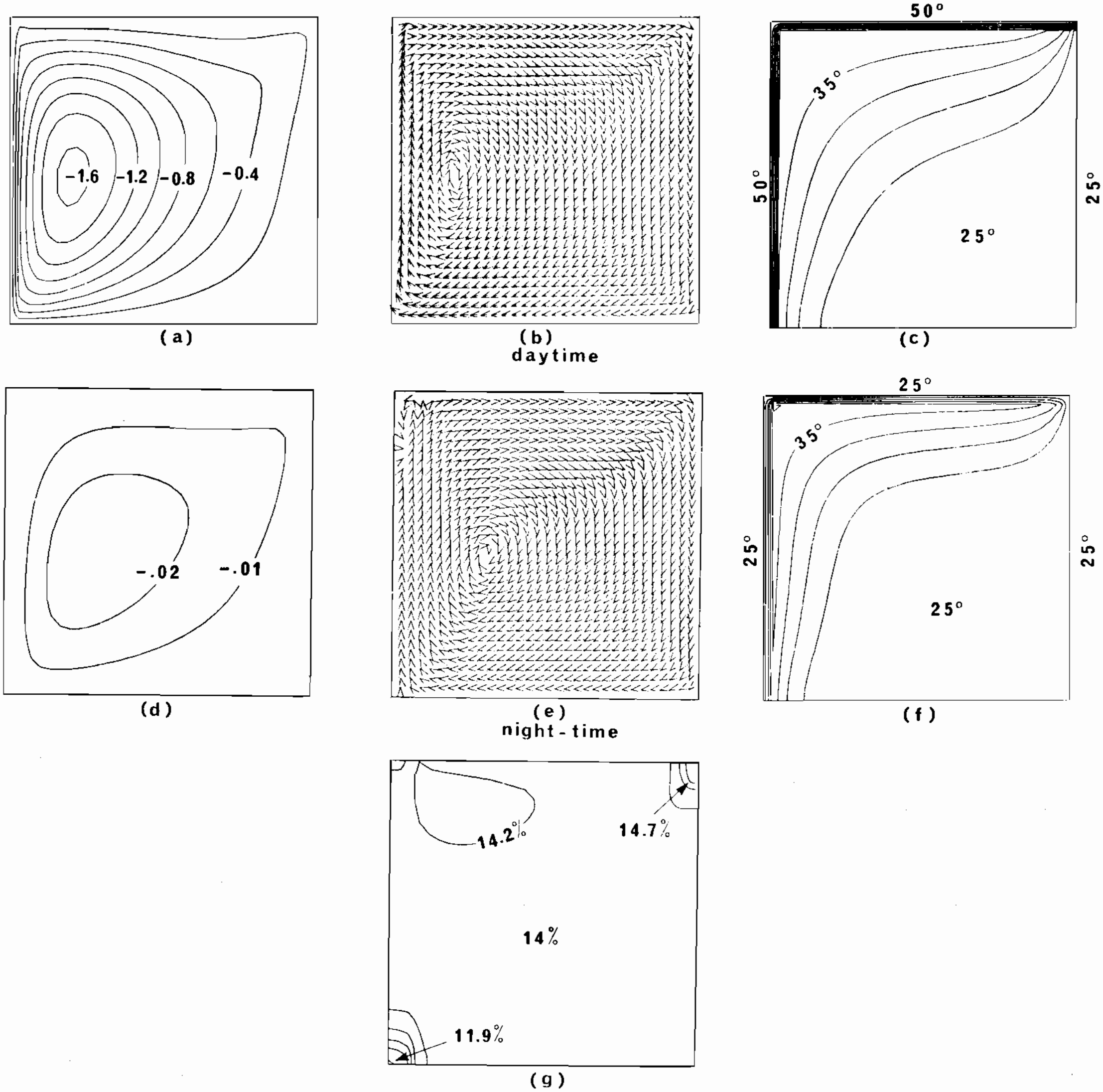

Fig. 2. Convective flow and temperature and moisture distribution in a rectangular grain bin with isothermal top after 12 months of storage. (a,d) streamlines; (b,e) velocity vector plots; (c,f) isotherms; and (g) moisture distribution.

and the temperature and moisture content distributions are as shown in Figure 2. The convection currents are similar to the previous case: strong during daytime and very weak during nighttime. As a result of the increased heat transfer area, a larger part of the grain store is affected by natural convection, as indicated by the isotherms. The region of increased moisture has moved to the right-hand corner and another wet spot has started to develop in the top left-hand corner.

If grain is stored at 18% moisture content (wet basis), the heat of respiration of the grain becomes quite significant (Figs 3 and 4). Convection currents now consist of one large cell occupying the whole store and two smaller inner cells, all rotating in the same direction. The strongest cell is still associated with the large temperature gradients along the hot wall. At nighttime, the circulation almost stops, except for a very weak current near the right-hand wall. The temperature of the grain bulk has risen from the initial value of 25°C to 35°C after only four weeks of storage.

In a bunker-type storage, grain is stored under plastic covers in the open. The grain is usually hot after harvesting at high temperature and the transfer of moisture by air convection currents is most serious at nights when ambient temperature is low. Figure 5 shows the simulation of a bunker with grain initially at 40°C and 10% moisture content. The temperature gradient along the sides causes cold, dense air to fall and displace hot, less dense air, which rises through the middle resulting in two distinct counter-rotating convection cells. The distortion of the isotherms by natural convection can be seen in Figure 5(c) and the redistribution of moisture in Figure 5(d).

Moisture is transferred to the region under the ridge from two lower regions along each side. It can be seen in Figure 6 that during the daytime natural convection ceases to be the dominant effect on moisture movement. Moisture may be diffused towards cooler regions as a result of the low water vapour pressure there, but there are no significant convection currents.

After another six months of storage (Fig. 5), the convection currents are more intense in the central region of the bunker and the influence of natural convection on the temperature distribution is

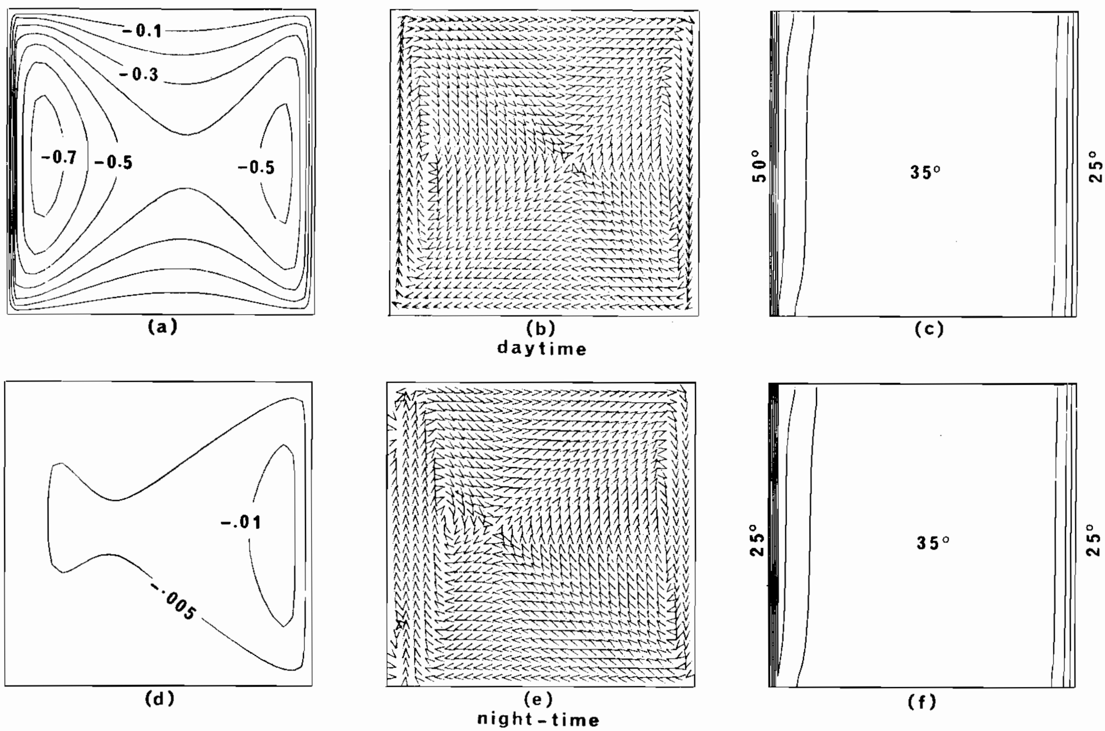

Fig. 3. Convective flow and temperature and moisture distribution in a rectangular grain bin with insulated top after four weeks of storage. Grain initially at 25°C and 18% moisture content wet basis: (a,d) streamlines; (b,e) velocity vector plots; and (c,f) isotherms.

more profound. Moisture redistribution now affects the whole bunker which contains an enlarged region of wet grain at the top and several dry regions below. With grain initially at 12% moisture content (w.b.), Figure 7 shows similar flow patterns, isotherms, and moisture distribution. The accumulation of moisture at the top region predicted in this study is consistent with observations in bunker storages in which caked and moulded masses of grain have been found along the ridge.

Conclusions

A transient state, two-dimensional numerical model has been presented to simulate the temperature and moisture changes by natural convection in grain stores. Airflow patterns, and temperature and moisture distributions were obtained by solving a set of simultaneous differential equations, assuming thermal and thermodynamic equilibrium. The study, carried out on a rectangular bin and a bunker-type storage structure under fluctuating thermal boundary conditions, offers an insight into the development of the flow and temperature fields and the redistribution of moisture in the grain bulk.

Acknowledgment

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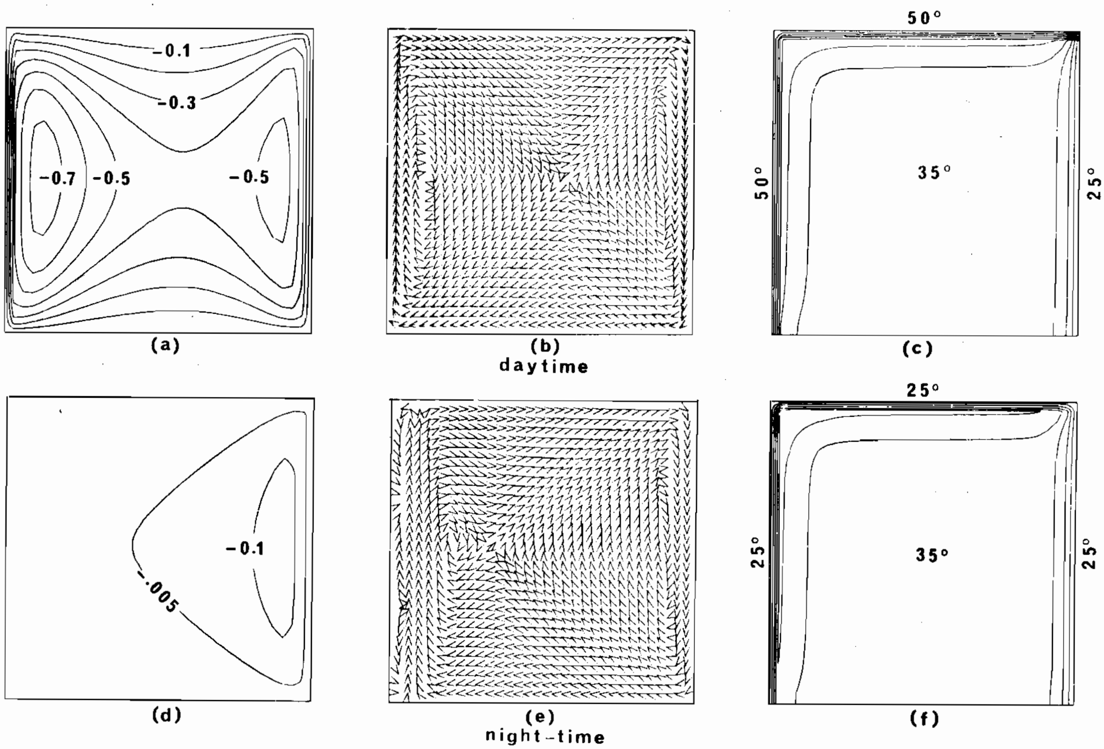

Fig. 4. Convective flow and temperature and moisture distribution in a rectangular grain bin with isothermal top after four weeks of storage. Grain initially at 25°C and 18% moisture content (wet basis): (a,d) streamlines; (b,e) velocity vector plots; and (c,f) isotherms.

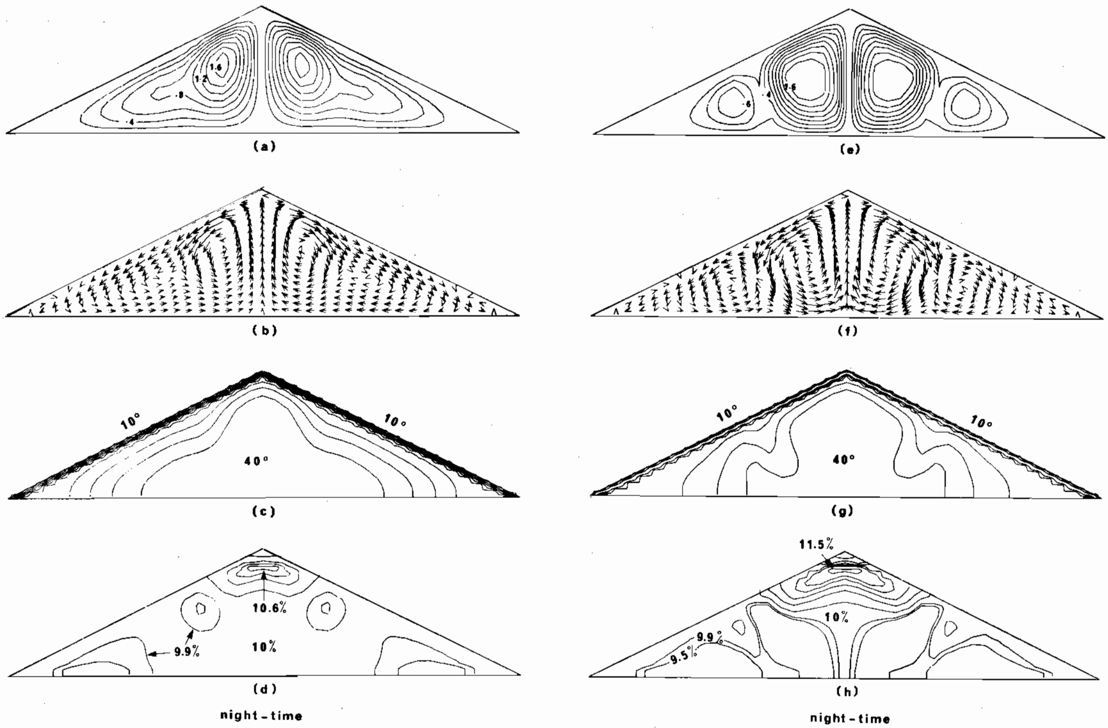

Fig. 5. Convective flow and temperature and moisture distribution in a bunker-type grain storage structure after 6 and 12 months storage: (a,e) streamlines; (b,f) velocity vector plots; (c,g) isotherms; and (d,h) moisture distribution.

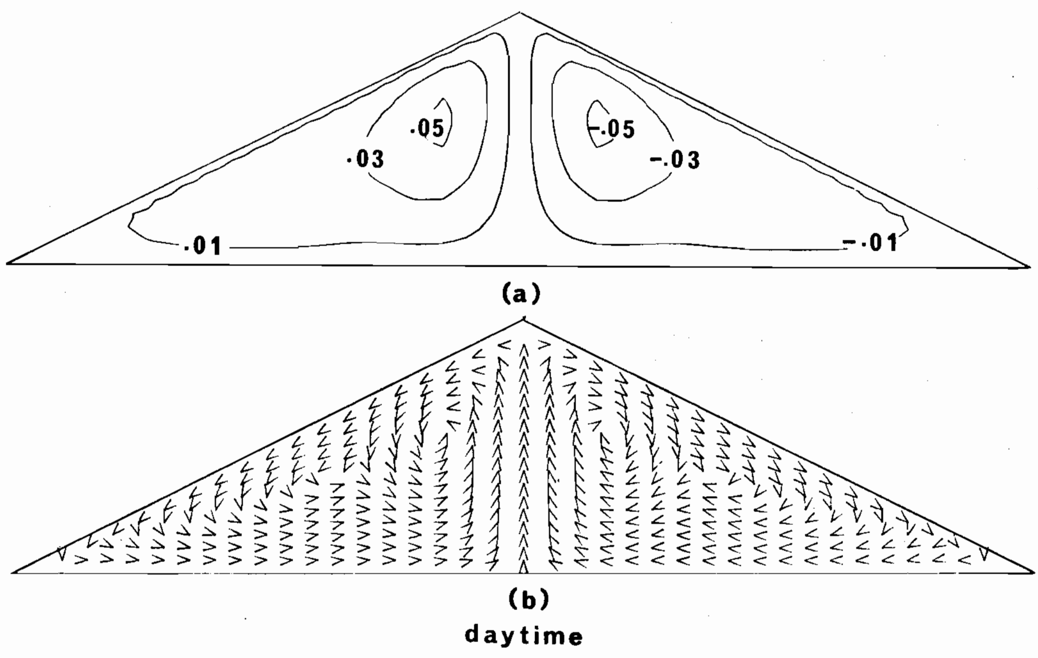

Fig. 6. Convective flow and temperature and moisture distribution in a bunker-type grain storage structure after six months storage: (a) streamlines; and (b) velocity vector plots.

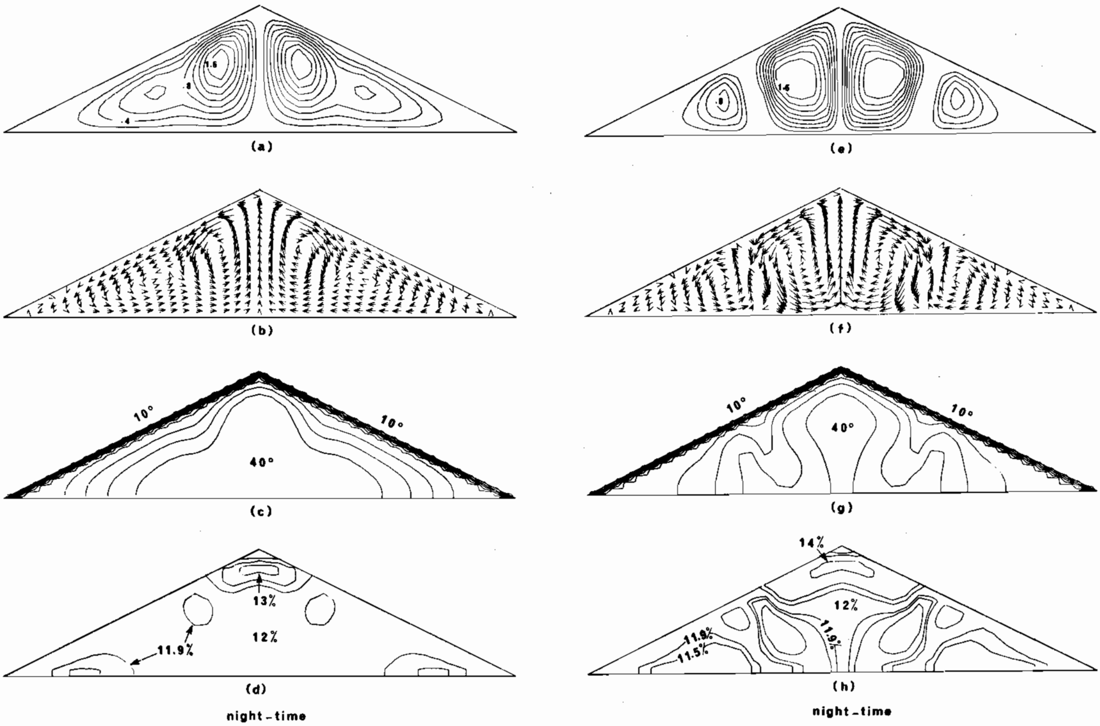

Fig. 7. Convective flow and temperature and moisture distribution in a bunker-type grain storage structure with grain initially at 12% moisture content (wet basis) after 6 and 12 months storage. (a,e) streamlines; (b,f) velocity vector plots; (c,g) isotherms; and (d,h) moisture distribution.

Nomenclature

c_a	specific heat of dry air at constant pressure	kJ/(kg dry air K)
c_m	specific heat of dry grain	kJ/(kg dry grain K)
c_w	specific heat of liquid water	kJ/(kg water K)
f_c	effective conductivity factor $= k^*/k_f$	—
g	acceleration due to gravity	m/s^2
h	enthalpy of moist air	kJ/kg dry air
h_s	latent heat of vaporisation of water in grain	kJ/kg water
h_v	latent heat of vaporisation of free water	kJ/kg water
H	enthalpy of moist grain	W/m/K
k*	effective conductivity of packed bed	W/m/K
k_f	thermal conductivity of air	W/m/K
L	height of bed	m
p	pressure	Pa
P	density of grain (kernel density)	kg/m^3
Pr	fluid Prandtl number	—
R	heat of respiration	W/kg
Ra	modified Rayleigh number $= \frac{g\beta\rho^2 c_a}{\mu}\frac{\kappa}{k^*}\Delta T\, L$	—
t	time	s
T	temperature	K
T_1	temperature of cold wall	K
T_2	temperature of hot wall	K
u	velocity in x direction	m/s
v	velocity in y direction	m/s
V	filtration velocity	m/s
w	air moisture content	kg water/kg dry air
x,y	coordinates	
W	grain moisture content (dry basis)	kg water/kg dry grain
β	coefficient of volumetric expansion	K^{-1}
ΔT	temperature difference $= T_2 - T_1$	K
ε	void fraction of packed bed	—
κ	permeability of packed bed	m^2
ρ	density of air	kg/m^3
μ	viscosity of air	$N\ s/m^2$
γ	$= \frac{P(1-\varepsilon)}{\rho\varepsilon}$	—
ζ	vorticity	s^{-1}

Modelling of Forced Convection in In-store Grain Drying: the State of the Art

F. W. Bakker-Arkema*

Abstract

An accurate simulation model of forced convection in-store grain drying will be an important tool for the engineering design of such systems. It will contribute to faster and more efficient designs of in-store grain drying installations for the humid tropics.

In-store grain drying models fall into two categories: (1) differential equation models, and (2) heat and mass balance models. Each can be further divided into non-equilibrium and equilibrium models. The author recommends the use of non-equilibrium, differential equation models for the use of in-store grain drying simulations because of their greater flexibility and accuracy, and more fundamental character.

Successful modelling of forced convection in-store grain drying requires a knowledge of the drying rate and equilibrium moisture content of cereals. The moisture diffusion and Guggenheim-Anderson-de Boer isotherm equations are recommended for these tasks. Development of quantitative grain quality models for the humid tropics is necessary if the effect of in-store drying on quality changes is also to be modelled.

DESIGN of forced convection in-store grain drying systems has until recently been by trial and error (Hall 1957). This mode of design is time-consuming and expensive; besides, the number of experimental tests which can be conducted annually is limited due to the short-time for which moist grain is available. Simulation modelling does not have these disadvantages.

Successful modelling requires an adequately accurate simulation model. If the model is to be used for optimisation and control as well as simulation, the model should be fast (in terms of computer time) as well as accurate (Brook and Bakker-Arkema 1980).

An in-store grain drying model can be used by the engineer as a design tool for (Brooker et al. 1974): (1) sizing of the dryer dimensions, (2) predicting the dryer performance, (3) evaluating operating-parameter effects, (4) investigating fan management, (5) scaling the dryer, (6) calculating the load and unload devices, (7) preliminary costing of the total in-store drying system, and (8) exploring dryer control strategies. If a grain quality model is added to the dehydration model, the effect of operating conditions on the grain quality can also be monitored (Bakker-Arkema et al. 1977).

In-store grain drying models can be classified as non-equilibrium or equilibrium models. In the equilibrium models, it is assumed that temperature (and sometimes also humidity) equilibrium conditions exist between the drying air and the grain at each level of the drying bed, and at each time period. Although the non-equilibrium models are more accurate, use of the simpler equilibrium models still appears justified for low airflow rate conditions (Sharp 1982).

This paper reviews the in-store grain drying models with respect to accuracy, ease of application to different crops, and computer time required. The relevance to the humid tropics is emphasised.

Differential Equation Models

Forced convection in-store grain drying models consisting of a series of differential equations are the most general of the models published in the literature. Both non-equilibrium and equilibrium type models are discussed.

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Non-equilibrium Models

A simulation in-store grain drying model can be developed by writing heat and mass balances on an arbitrarily selected control volume of thickness Δx in the dryer, along with the appropriate rate equations (Brooker et al. 1974). This results in differential equations for the air absolute humidity (H), the air temperature (T), the grain temperature (θ), and the average moisture content ($\overline{M}$):

$$\frac{\partial T}{\partial x} = \frac{-ha}{G_a c_a + G_a c_v H}(T - \theta) \qquad (1)$$

$$\frac{\partial \theta}{\partial t} = \frac{ha}{p_p c_p + p_p c_w \overline{M}}(T - \theta) + \frac{h_{fg} + c_v (T - \theta)}{p_p c_p + p_p c_w \overline{M}} G_a \frac{\partial H}{\partial x} \qquad (2)$$

$$\frac{\partial H}{\partial x} = - \frac{Gp\partial \overline{M}}{G_a \partial t} \qquad (3)$$

$$\frac{\partial \overline{M}}{\partial t} = \text{a thin-layer drying or diffusion equation} \qquad (4)$$

Equation (4) can be an empirical thin-layer drying rate equation or a theoretical diffusion equation, with the drying rate constant (k) or the effective diffusion coefficient (D) as a function of temperature and moisture content (Bruin and Luyben 1980). This is essential if the tempering process is modelled in paddy (Bakker-Arkema et al. 1984).

The terms $\partial T/\partial t$ and $\partial H/\partial t$ in Equations (1) and (2) are small and have been neglected by several investigators in order to speed up the computer solutions (Bakker-Arkema et al. 1974; Spencer 1969). However, Laws and Parry (1983) included the terms in their generalised in-store drying model.

In solving Equations (1) through (4) by finite difference techniques, the grain bed is divided into layers of thickness Δx equal to 0.01–0.1 m; the air and grain properties are assumed to be uniform in each layer during each time step. The outlet air conditions of a layer are used as the inlet conditions to the subsequent layer. The solution is obtained by stepwise numerical integration along the space (x) and time (t) co-ordinates. The time step Δt depends on the flow rate of the air and the drying rate of the grain; it varies from 1 to 100 sec (Bakker-Arkema et al. 1974).

The accuracy of the solution is improved if the shrinkage occurring in the bed during in-store drying is accounted for (Spencer 1969).

In general, the non-equilibrium partial differential equation model is of greater accuracy and applicability over a wider range of in-store drying cases than the equilibrium models to be discussed in the next section (Sharp 1982). The greater flexibility comes at the expense of increased computer time. However, since computer technology continues to develop rapidly in terms of memory cost and computing speed, it is expected that even personal computers will soon be able to rapidly solve the non-equilibrium simulation model of in-store drying.

Equilibrium Models

In-store equilibrium grain drying models are a simplification of the non-equilibrium model described by Equations (1) through (4). By assuming equilibrium between the air and grain temperatures ($T = \theta$), as is the case in low airflow rate, low air-temperature drying, Equations (1) through (4) are condensed to a three-equation model (Bakker-Arkema et al. 1976):

$$G_a \frac{\partial H}{\partial x} = - \rho_g \frac{\partial \overline{M}}{\partial t} \qquad (5)$$

$$G_a(c_a + c_v H)\frac{\partial t}{\partial x} = - \rho_p(c_p + \overline{M}c_w)\frac{\partial T}{\partial t} - G_a((c_v - c_w) T + h_{fg})\frac{\partial H}{\partial x} \qquad (6)$$

$$\frac{d\overline{M}}{dt} = \text{thin-layer drying or diffusion equation} \qquad (7)$$

The thermal equilibrium model can be further simplified by assuming instantaneous thermal *and* moisture equilibrium between air and grain at each point within the grain bed at any time during the drying process due to infinite convective heat and mass transfer coefficients. This assumption leads to a two-equation in-store grain drying model (Parry 1985).

Hukill (1954) proposed a one-equation in-store drying model obtained by combining Equations (2) and (3), and assuming the latent heat to be much larger than the sensible heat, and ρ_p to be constant. This results in the so-called logarithmic in-store drying model:

$$G_a c_a \frac{\partial T}{\partial x} = \rho_p h_{fg} \frac{\partial \overline{M}}{\partial t} \quad (8)$$

By relating the travel rate of the drying zone to airflow rate, Hukill was able to obtain an analytical solution of Equation (8) for the dimensionless moisture content in the grain bed as a function of the dimensionless depth and time variables. Solutions of Equation (8) with various initial and boundary conditions have been used by Ohio State University researchers (Barre et al. 1971; Keener et al. 1978) to analyse several in-store grain drying systems. The simplicity of the Hukill (or logarithmic) models is their only advantage.

Heat and Mass Balance Models

Boyce (1966) and Thompson et al. (1968) independently presented an algebraic model for forced convection in-store grain drying based on heat and mass balances on thin layers of grain; the model allows layer by layer calculation of the temperatures and moisture contents of grain and air in the drying bed. The original model was later modified by assuming heat and mass transfer equilibrium between the air and the grain in each layer (Thompson 1972). Several versions of the equilibrium and quasi-equilibrium heat and mass balance models have been used in the past decade with varied success to analyse low-temperature grain drying systems (Sutherland et al. 1971; Bloom and Shove 1971; Pfost et al. 1977; Morey 1979; van Ee and Kline, 1979; Mittal and Otten 1980; Pierce and Thompson 1980). The accuracy of the predictions has been restricted by the assumptions made in the derivation of this model type (Parry 1985).

Heat and mass balance drying models have made significant contributions to drying technology mainly because of their simplicity and computation speed (Sharp 1982). The differential equation models are more accurate and theoretically sounder since they are based on the laws of heat and mass transfer and of thermodynamics. In addition, increased computer power has made the differential equation models suitable for operational research applications.

Auxiliary Simulation Properties

The application of the forced convection in-store grain drying simulation models requires auxiliary information on grain, bed and air properties ranging from kernel drying rate to bed static pressure and air-moisture psychrometrics. If grain quality is a critical criterion, a grain-deterioration or spoilage model should be an integral part of the in-store grain drying models.

Grain Properties

The in-store grain drying model of Equations (1) through (4) shows which thermo-physical grain property values are required for solution of the model. They include the density, the bed porosity, the heat of vaporisation, the convective packed-bed heat transfer coefficient, the specific surface area, the specific heat and the static pressure.

Data and equations of these properties for grains and legumes have been collected by several investigators (Rao and Pfost 1980; Brook and Foster 1981; Hague et al. 1982).

Drying Rate Equations

In order to model the drying of a bed of grain, the drying rate characteristics of the individual kernels have to be known for different drying conditions. The drying rate equation fulfills this purpose.

In the past decade, hundreds of papers have been published on the drying of capillary-porous rigid particles such as grains. Few are relevant to the engineering design of drying systems. Since several exhaustive reviews on the fundamental aspects of the drying of food materials have recently been published (van Brakel 1980; Bruin and Luyben 1980; Toei 1983), this paper reviews only those equations which have proven to be effective in the actual design of in-store dryers.

The drying of grain kernels is due to various transport mechanisms. Moisture movement can be caused by liquid diffusion, vapour diffusion, thermal diffusion, capillary flow, internal evaporation and condensation, surface diffusion, shrinkage pressure, or, most frequently, a combination of these mechanisms. Since knowledge of the exact mechanisms in grain drying is still limited, the choice of one mechanism (and thus one equation) over another (and thus, another equation) for the interpretation of the drying rate data appears nonsensical to the design engineer. What he desires is an equation that represents correctly the moisture and heat transfer behaviour of the grain kernels in a certain temperature/humidity range.

The drying theory of individual particles has developed from the empirical drying rate equation of Fisher (1923) to the liquid diffusion equation of Gilliland and Sherwood (1933), the capillary movement equation of Ceaglske and Hougen (1937), the vapour diffusion/capillary liquid movement equation of Krischer (1938), the evaporation-condensation theory of Henry (1939), and finally the irreversible thermodynamic equations of Luikov 1966). Recent theoretical drying papers by, for example, Fortes and Okos (1980) and Whitaker (1980) appear to offer nothing fundamentally new on the subject. The best critique on the plethora of so-called 'fundamental' papers on the topic of mass transfer in convective drying of porous media is by van Brakel (1980).

Due to the complexity of the drying process, engineers prefer to lump the effects of the different drying transport mechanisms into a simplified moisture diffusion equation with a concentration and temperature dependent diffusion coefficient (D). For a spherical or quasi-spherical non-shrinking kernel:

$$\frac{\partial M}{\partial t} = \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 D \frac{\partial M}{\partial r}) \qquad (9)$$

The D-value is the apparent or effective diffusion coefficient with an Arrhenius type temperature dependency:

$$D = D_o \exp (- \frac{E}{R\,T_{abs}}) \qquad (10)$$

where E is the energy of activation. Values of the diffusion coefficient for some grains at different moisture contents (e.g. paddy, maize, wheat) have been tabulated by Bakker-Arkema et al. (1983b) and Steffe and Singh (1982). Unfortunately, knowledge of the precise dependence of the moisture diffusivity on temperature and moisture content of grains is limited, and this often forces engineers to employ empirical drying rate equations for the simulation models of in-store grain dryers.

The drying rate of cereals is frequently expressed in the literature by a semi-empirical relationship, the so-called 'thin-layer' equation, which relates the standardised average moisture content to time:

$$\frac{\overline{M} - \overline{M}_e}{\overline{M}_i - \overline{M}_e} = \exp(-kt) \qquad (11)$$

where k is a product constant dependent on temperature and is called the 'drying constant' with dimension equal to s^{-1}. (k can thus be interpreted as the ratio of the diffusion coefficient divided by a characteristic length squared.) Values of k for different grains can be found in Brooker et al. (1974).

In comparing Equations (9) and (11) for engineering applications, the diffusion Equation (9) is preferred since it allows calculation of the moisture profiles within a grain kernel. (Equation 11 only calculates the average moisture content.) Thus, the diffusion equation can simulate the change in the moisture distribution within the paddy kernels during periods of tempering.

Sorption Isotherms

To solve the drying rate equation discussed in the previous section, the boundary conditions need to be specified in terms of the moisture sorption isotherm which expresses the average moisture content of a grain kernel as a function of the environmental temperature and relative humidity. The literature abounds with papers on the sorption phenomena of food products (e.g. Chirife and Iglesias 1978; Pixton and Howe 1983). In fact, publication of such papers appears to continue unabated (Chinnan and Beuchat 1985). The purpose of this activity is not evident since, for design purposes, sufficient information appears to be known on the topic.

A consensus has developed recently among scientists and engineers of the superiority of the Guggenheim-Anderson-de Boer (GAB) equation for the prediction of the water activity (a_w) of food products (van den Berg 1984). The GAB equation has the following form:

$$\overline{M} = \frac{\overline{M}_o CK}{(1 - Ka_w)(1 - Ka_w + CKa_w)} \qquad (12)$$

where $\overline{M}_o$ is the moisture content at monolayer coverage; and C and K are empirical temperature-dependent product constants.

Lamauro et al. (1985) recently compared several sorption isotherm equations for different products including grains. They concluded that the GAB equation gives a good fit for over 75% of the products studied, and describes the isotherms better than the two-parameter equations. The values of $\overline{M}_o$, C and K in the GAB equation for 163 biological products are tabulated in the Lamauro papers for a limited temperature range.

For grains, the two-parameter Chung-Pfost isotherm equation has proven to be effective in the simulation of different dryer designs (Sokhansanj 1984):

$$\ln a_w = - \frac{K_1}{R\,T_{abs}} \exp(- K_2 \overline{M}) \qquad (13)$$

where K_1 and K_2 are product constants. Values for the two constants of the major grain species over the full range of temperatures encountered in the grain drying process have been tabulated by Pfost et al. (1976).

The GAB equation has a theoretical basis, and thus supplies fundamental information on the thermodynamic properties (e.g. heat of vaporisation, pore structure) of a grain (Zuritz and Singh 1985). In contrast, the Chung-Pfost relationship is empirical in nature. Which equation is better for design depends on which relationship represents the experimental data best within the range of moisture contents and temperatures encountered in the dryer under study. The importance of the equilibrium moisture content in simulation has been illustrated by van Ee and Kline (1979) who showed that a 0.5% change in the equilibrium moisture content of maize has a significant effect on the simulated values of the final grain moisture content and the rate of movement of the drying front, in in-store drying installations.

Psychrometrics

Modelling of the thermodynamic properties of air as it passes through the bed of grain is an integral part of the in-store grain drying simulation. The relationship between dry-bulb temperature, relative humidity, absolute humidity, density, specific volume, enthalpy, dew-point temperature and wet-bulb temperature are given in Brooker et al. (1974). A package of psychrometric subroutines called SYCHART, representing the psychrometric chart in SI units can be found in Bakker-Arkema et al. (1978).

Grain Quality

The objective of grain drying is to dry grain without affecting the desired grain qualities. It depends on the end-use of the product which quality characteristic needs to be conserved; for paddy, head yield is the major criterion, for wheat, baking quality. In an exhaustive and excellent review on heat damage to cereal grains, Nellist (1982) recommended a more systematic approach to the topic than has been the case in the past.

For optimum design and control of grain drying equipment, it is necessary to quantify deterioration in grain quality. In the objective function, the quality deterioration of the grain acts as a penalty function. Although many data on the subject can be found in the literature, modelling of the physical condition of a biological product is not well-developed, except for some empirical relationships for the breakage increase of maize (Brook 1977), for the moulding of maize (Morey 1979), and for the baking quality of wheat (Nellist 1978).

Different quality criteria have been used for dryer design. Ghaly and Taylor (1982) monitored the micro-baking loaf volume, the turbidity, and the viability during the thermal disinfestation of wheat. Ghaly and Sutherland (1983) measured free-fatty acid content and oil yield during the high-temperature drying of soybeans. Mühlbauer et al. (1976) considered lysine content and colour in evaluating maize dried at high temperatures. Other quality design criteria considered include head yield of rice (Fontana 1983), breakage susceptibility of maize (Kusterman and Kutzbach 1981, and mould development in maize (Mühlbauer et al. 1981). It is necessary to develop quantitative models similar to the first-order kinetic equation for viability loss by Schreiber et al. (1981) for the change of each of these quality criteria occurring during drying, and link them to the mass and heat transfer in the in-store drying models.

Simulation is an essential tool in the design of in-store grain drying systems for the tropics. Differential equation models are more accurate and flexible than other types of models. The necessary auxiliary equations are available in the literature for the major cereal crops such as rice and maize.

List of Symbols Used

- a specific product surface area, m^{-1}
- a_w water activity, decimal
- c specific heat, kJ/kg°C
- d diameter, m
- h convective heat transfer coefficient, kJ/s m^2 °C
- h_{fg} heat of vaporisation, kJ/kg
- k drying constant, sec^{-1}
- P_{at} atmospheric pressure, N/m^2
- r kernel coordinate, m

t	time, s
x	depth coordinate, m
C	product constant
D	effective diffusion coefficient, m^2/s
G	dry weight flow rate, kg/m^2s
H	humidity ratio, kg/kg
K	product constant
M	local moisture content within kernel, dry basis (decimal)
$\bar{M}$	average moisture content, dry basis (decimal)
R	equivalent kernel radius, m
T	air temperature, °C
T_{abs}	absolute temperature, K
V	velocity, m/s
θ	grain temperature, °C
ε	void ratio, decimal
ρ	density, kg/m^3

as a subscript:

a	dry air
e	equilibrium
i	initial
p	dry grain
r	radial
t	at time t
v	water vapour
w	water (liquid)

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Basic Principles of Aeration and In-store Drying
Session Chairman's Summary

C.W. Bockhop*

THE four papers presented during this session provided an excellent discussion of the basic principles of drying and storage, as well as of aeration of grain in storage. The problems were well defined.

The modelling of the temperature and moisture changes and the natural convection that occurred in grain storage structures was well illustrated in the third paper.

A good case was made for modelling of the forced convection in grain drying by Dr Bakker-Arkema who, through illustration, pointed out the value of proper modelling in the designing of drying systems.

In discussing Dr Driscoll's paper on the application of psychrometrics to grain drying, Dr Thorpe endorsed the strategy proposed for four-stage drying and cooling of wet grain, i.e. a holding stage, a drying stage, final drying, and a holding stage. He pointed out, however, that there need be little concern about the re-moisturising of grain under natural aeration, even under tropical conditions where the air moisture content is 0.02 kg of water/kg of dry air. This is because the aeration flow rate, typically 1 litre of air per second per tonne, is incapable of adding much moisture to a bulk of grain. Only that grain very close to the air inlet will be re-wetted. To prove this, simply do a mass balance over the grain mass. Moisture uptake by diffusion is also a very slow process. It could take decades for a grain bulk with linear dimensions of 10 m x 10 m x 10 m to reach an equilibrium with its environment.

Following Dr Nguyen's paper there was some discussion on the speed of natural air movement, which was reported to be in the range of 1 mm per second.

Also, the question was raised on how to prevent natural circulation and the formation of high moisture pockets. This can be alleviated by smaller storage structures, by sealed storage, and by cooling the grain.

A question was raised on the respiration rates cited in the paper. It was agreed that more information on respiration rates is needed. Loss of mass is not so important in low temperature drying. More important is development of proper theory concerning the growth of microorganisms.

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Design of Aeration and In-store Drying Systems

Design Parameters for Storage and Handling Systems for Grain

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Abstract

Parameters are constants that define functional mathematical relationships. This paper explains the use of parameters of air psychrometrics, grain hygroscopicity, rates of dry matter loss and insect increase, resistance of grain to airflow, economics of grades and handling costs, and probability analysis of percentage loss data, for designing large and small storage systems in the humid tropics.

Controlled ventilation of both bulk and bagged storage shows economic benefits that should bring about the construction of tight storage buildings with forced ventilation by either ambient or conditioned air.

PARAMETERS are for measuring. In relation to grain storage, parameters are the constants that define the additive, multiplicative, and exponential and their inverses the subtractive, divisive, and logarithmic relationships between air, grain, and markets. Parameters for air are well known and vary little. Those for the physical and biological properties of grain are only partially known. Those for the economics of marketing are historically, politically, and sociologically variable according to the circumstances of the marketing system. Parameters are numbers, dimensional or non-dimensional, that make it possible to quantitatively design the properties that qualitatively enhance the value of stored grain. A.D. Gracey (personal communication) stated that the design should keep the grain dry, clean, pest-free, secure, handy, and whole. This paper is written to assist in rationalisation of design to meet these criteria.

Equations for the capacity, power, and strength characteristics of handling equipment are given by Teter (1981), who converted the equations published by Henderson and Perry (1976) into SI units. Some equations for air properties, grain properties, economic properties, and statistical properties are given in the Appendix in Basic computer language. These equations are of use to the engineer, but design of grain storage is not exclusively the milieu of the engineer. General specifications for storage should be drawn up by managers of grain handling systems whether they are farmers, millers, or middlemen. Baille (1982) presented categories of specifications which may be rationalised by engineers using parameters for the interrelated properties of air, grain, moulds, insects, and economics.

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Air Properties

Donald B. Brooker (1967) deserves credit for making his and others' psychrometric work available in the ASAE Yearbook of Standards (ASAE 1984). The program, AIRPSY (see Appendix), presents the psychrometric equations with their parameters and solutions. In addition to the usual psychrometric air properties. the deterioration index, DI, suggested by Brooks (1950) and defined by line 530 of AIRPSY, is included in air properties. Since this index skillfully combines temperature and relative humidity into one descriptive term that is related not only to multiplication of microorganisms and insect population dynamics, but also to equilibrium moisture content and rate of dry matter loss, it is useful in both design and operation of storages.

In using the air properties equations, care must be taken regarding the total atmospheric pressure of the air. AIRPSY line 250 defines this pressure as 101.325 Pa, a pressure that may be changed according to the altitude at which the calculations are made. Engineers make calculations at a constant pressure, a condition that seldom exists because wind and convection testify to the variability of total air pressure between two locations, even within the same structure. Neither convection currents nor moisture migration exist when total pressure is actually constant throughout a building. This point is made because texts differ on whether the ratio of vapour pressures, or the ratio of humidity ratios define the relative humidity of air. If total air pressure is constant, then the relative humidity is the ratio of the vapour pressure in the air to the vapour pressure at saturation of the air at this same total pressure. If, in the process of being saturated, the total pressure of the air changes, the ratio of the vapour pressures is the same as the ratio of the weights of vapour associated with weight of dry air, eliminating the need to define the difference between relative humidity and degree of saturation, a term sometimes used for the ratio of kg of water vapour in one kg of dry air to the kg of water vapour at saturation in one kg of dry air.

Either simulation, as that presented by Chang et al (1979), or data analysis of aeration and/or in-bin drying, may need the format of AIRBAL (Appendix), which contains no parameters since it is a 'book-keeping' computation, and not a definition of relationships. Both AIRPOW and AIRVEL use well known constants of the acceleration of gravity (9.807), the seconds in a minute (60), and the kg m per s mechanical equivalent of kW (102.2). But they may be more readily used in design when the equations are rewritten using parametric constants such as specific volume and pressure.

Dry Matter Loss

Dry matter loss of grain is an oxidative process accompanied by the release of carbon dioxide, water, and heat. It is also accompanied by deterioration in grain quality which may result in visibly damaged kernels, a factor of grain grade and usually grain value. The oxidation may be caused by respiration of microorganisms, embryos, insects, or rodents in the grain. The constants of the oxidation are: for 1 kg of dry matter lost from a cereal grain, 1.07 kg of oxygen is used and 1.47 kg of carbon dioxide, 0.60 kg of water, and 15.7 MJ of heat are released. The process of ventilation or aeration removes the heat and the water generated in the process of oxidation or deterioration. Thus, design aeration rate depends upon the rate of dry matter loss and the properties of the air. Rate of dry matter loss (DML) is commonly expressed as %DML/day. Two different equations with the attendant parameters for paddy are compared by the programs called DMLFAO as taken from Hall (1975) and DMLKSU as taken from Seib et al. (1980). They are given in the Appendix. A check between the output of the two will show considerable percentage difference, especially for paddy below 15% moisture content, but since the rates of respiration are quite low at these moisture levels, the error is not alarming in practice. DMLFAO also shows the laboratory results of Bailey and Gurjar (1920) for brown and milled rice. Design of paddy aeration in m^3/tonne min, 'q', made according to DMLFAO has been satisfactory in the humid tropics; therefore, this method was used for programming DMLEMCDI, the program that relates %DML/day to percentage equilibrium moisture content (EMC) and deterioration index; an interrelation between respiration, grain hygroscopicity, and climate. DMLHRS is the same as the KSU equation, but it is solved for hours when a given dry matter loss is entered into the program. This determines the 'allowable hours' for storage if the acceptable level of %DML is known.

Economics

Grain must be dried soon after it matures if its value as food or feed is to be retained. This value loss is reflected in the visibly damaged kernels which appear in time for moist or wet grain (15.5 to 30% moisture content); furthermore, moist and especially wet grain loses viability rapidly. Economic losses of value, damaged kernels, and germination are programmed in ECOPL. The value loss of paddy is taken from the Malaysian grade standards and prices for rice milled from paddy having different levels of % damaged kernels. The increase in damaged kernels in 10 days is taken from classroom laboratory exercises where students recorded the visibly damaged kernels in paddy at moisture contents from 14% to 25% held for 10 days, sealed and unsealed. The germinability is taken from studies of Roberts (1961). More economic studies of this nature are needed to accurately estimate the 'penalty cost' for failure to properly dry and to keep grain dry.

Harry Th. L. van Ruiten developed a technique of estimating the profit of various rice blends if the value and out-turn of head, large brokens, and small brokens are known and are compared with the value of various sale grades having given constituents of head, large, and small brokens. Since fissuring causes loss of head rice, and consequentially loss of sale value, this economic study may be used to evaluate the risks taken by possible rewetting of paddy by use of aeration. ECORBLD, or a program similar to it, may be used to optimise the profit from rice blending.

Two unique features of the program ECOTCOST are that the transport costs are expressed in terms of the percentage value of the product used in transportation, and the percentage value of the product at any geographic point is computed as the 'price surface' of this location, giving data for locating buying and processing plants to maintain a desired price level. The model is valid for any product and transportation costs as long as these are accurately known, so that the proper parameters may be inserted. The intersection of price surfaces between competing procurement centres forms the boundary of equal sale opportunity between the competing centres.

ECOWT uses the parametric difference between moisture content on a wet basis and on a dry basis to show the true weight difference occasioned by drying. A 5% change in moisture is not a 5% change in weight.

Physical Grain Properties

GRAER gives a design rate for aeration of maize and paddy, 'q', m^3/tonne min. Grain may be aerated when the equilibrium moisture content (EMC) of the air is below the moisture content of the grain. To bring the air into a 'safe' storage moisture, the air should have a deterioration index (DI) of 3.8 or less for maize, and 5.0 or less for paddy. This concept is explained in greater detail by Teter (1982). If the diurnal variation of the DI is not available in the records, but an estimate can be made of the average daily relative humidity, the program estimates the hours that fans may be operated each day by assuming that the daily relative humidity resembles a sine curve. This is an assumption that is not borne out well by weather data, which show the daily variation in relative humidity to be less symmetrical than the sine wave. If the program shows that aeration is not possible, dehumidifying the air by use of supplemental heat, mechanical condensation of water, or chemical absorption is necessary. Some climates of the humid tropics are too wet for too long to make natural air aeration practical for cereal grain.

The resistance of grain to airflow, the airflow rate, and the practical static pressure limits on the aeration fan determine the design depth of grain storage. GRDEPTH computes the allowable depth of design, a practical matter in the selection between horizontal and silo storage. GRDEPTH as given applies only to paddy. An inverse of GRDEPTH, GRSPR, gives the Pascals of pressure for a given depth of grain subjected to a given air flow, 'q'. The parameters for resistance of grain to airflow may be calculated from the curve fitting program, SOL; then these parameters may be used in GRDEPTH to give a program for other grains.

GREMC contains the parameters for the EMC of the 11 grains listed for the Chung-Pfost EMC equation given in ASAE (1984). The program gives either the EMC when the °C and %RH are entered, or the %RH when °C and EMC are entered. The programs GRDK, GRGER, and GRVAL are the same as those given in ECOPL.

Insect Population Dynamics

Estimations of population increase of insects may be used to optimise fumigation and to estimate benefits or losses wrought by environmental control. Some evidence indicates that *Sitophilus* spp. have a maximum rate of increase at a DI of 2.9, too dry for moulding to be a serious threat to grain. Thus, insect increase in the warm tropics may be highest at the climate for optimum storage moisture. Two models are presented for insect population dynamics for *Sitophilus oryzae*. The first, INSINC, assumes that the grain is in equilibrium at the input DI; the second, INSINC2, inputs the actual moisture content and is modelled after the work of Evans (1982). Both models assume that the rate of population increase is normally distributed as a function of the environment. This preliminary work for maize and wheat shows some promise for design and operation of insect control in structures. The gaseous environment factor has not been given parameters.

Statistics

Statistical parameters have special meaning in design of storage and handling systems. The usual agricultural statistics method of referring to two data sets as being significantly or highly significantly different is not satisfactory for decision making in design. When a study is made of two systems, the difference between systems under study should be expressed as a probability of difference, which may range from 0.5 to 1.0, 0.5 being the probability that there is no difference between the two systems. The program STAT is taken from the equation for the normal curve given in line 50 of the program, and the parameters given by Abramowitz and Stegun (1964) for the area under the normal curve. The program calculates the area under the normal curve when the value of the number of standard deviations from the mean is entered. For any two normally distributed sets of data, the intersection of the two data distribution curves is the difference between the means of the two sets divided by the sum of the standard deviations of the two sets. This gives a direct reading of probability of difference which may be evaluated for design. If one system is better than another with the probability of 0.55 or more, and the systems cost the same, it is logical to select the system that is probably superior.

If the criterion for study is a percentage such as percentage loss, the data are not normally distributed, but have a markedly severe skew towards zero. The data must be transformed to a normal distribution for analysis of variance, and after the estimate is made for the variance of the transformed values, these parameters must be reconverted to the original percentage loss data. This process is tedious without the computer, but program STATP is designed to make these transformations, computing the standard deviations and reconverting them to percentage loss. Note that the standard deviation to the right of the mode is not equal to the standard deviation to the left for skewed data. The test for probability of difference is slightly different for skewed data because the input value 'x' into STAT is now the difference between the means divided by the sum of the standard deviation to the right of the lesser set plus the standard deviation to the left of the greater set.

Solutions for Parameters

Considerable data are available that may be converted to parameters for use in the computer. For example, the ASAE Yearbook (ASAE 1984) contains a number of curves for the resistance of grains to airflow. For design, these curves may be estimated as straight line segments of log x vs. log y curves. SOL is a curve-fitting program which may be used to rapidly find the parameters of resistance for any grain published by taking points on the curve at intervals judged suitable for straight line log-log relationship.

Future Storage Designs

Controlled ventilation of both bulk and bagged storage shows economic benefit that should bring about the construction of many more 'tight', even oxygen limiting, storage buildings in the future. Where ambient conditions preclude the feasibility of aeration or controlled ventilation, the conditioning of the air to bring the deterioration index to a level that is suitable for aeration should become a part of design considerations.

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APPENDIX: DESIGN PARAMETERS FOR STORAGE AND HANDLING SYSTEMS FOR GRAIN

The following computational programs in the Basic language are examples of the use of parameters in designing grain storage and handling. The names and brief descriptions of the programs are followed by the printouts of the actual computational routines.

AIRBAL: Demonstrates a sub-routine useful in analysing work done by observed air properties in and out of bins, and also in simulation of drying and aeration where heat and water exchanges are made between grain and air.

AIRPAS: For an input of temperature in °C gives the Pascals of vapour pressure at saturation.

AIRPOW: Air power is printed when the total Pascals of pressure, the specific volume and the air delivery are entered.

AIRPSY: From an input of dry bulb temperature, °C, and wet bulb temperature, °C, gives:
Pascals of vapour pressure at saturation at dry bulb, C°
Pascals of vapour pressure at saturation at wet bulb, C°
Latent heat of vaporisation, J/kg of dry air
Pascals of vapour pressure in the air
Relative humidity, %
Specific volume of air, m^3/kg of dry air
Humidity ratio, kg of water/kg of dry air
Dew point temperature, °C
Deterioration index
Enthalpy, J/kg of dry air.

AIRVEL: Computes the velocity of air when the specific volume and velocity pressure of the air is known.

DMLEMCDI: Computes the equilibrium moisture content of paddy for a given deterioration index and then estimates the %DML (Dry Matter Loss)/Day for paddy in equilibrium with the ambient climate.

DMLFAO: Estimates dry mater loss, %DML/Day, for paddy, maize, brown rice, and rice using curves published in an FAO manual by Hall (1975) and data taken by Bailey and Gurjar (1920).

DMLHRS: Computes hours estimated for long and medium grain paddy to have a given %DML when stored at a given temperature, °C, and % moisture content.

DMLKSU: Computes dry matter loss of long and medium grain paddy using inputs of time, moisture content and temperature (from Kansas State University).

ECOPL: Estimates % value loss of paddy of a given moisture content in a given number of days, the % damaged kernels of a given moisture content in 10 days, and the loss of germination.

ECORBLD: For a given mill output estimates the value of rice blends of given grades when the market prices are known. This is developed from the work of Harry van Ruiten.

ECOTCOST: Computes the price surface, that is the % value of paddy or rice at a given geographic location related to the place of '100% value'. Parameters must be changed to fit the conomics of the geographic location.

ECOWT: Given the initial moisture content and wet of wet grain, computes the dried weight of the grain.

GRAER: Prints a recommended rate of aeration, 'q', (m^3/tonne min) for paddy or maize stored at a given moisture content when either the allowable hours per day of fan operation or the 24 hour average relative humidity is known.

GRDEPTH: Estimates the depth of paddy for a given aeration rate, 'q', and Pascals of static pressure.

GRDK: Estimates the increase in visibly damaged kernels in paddy held for 10 days at a moisture content above 15%.

GREMC: Calculates the equilibrium moisture content (EMC) of 11 grains for a given temperature, °C, and either % relative humidity, or % moisture content, using the Chung-Pfost equation.

GRSPR: Gives the Pascals of pressure required to aerate paddy placed at a given depth and subjected to a given air flow, 'q'. May be expanded for other grains.

GRSPR2: Same except for brown rice and rice.

GRVAL: Estimates the % value of paddy held for an input number of days at an input moisture content above 15%.

INSINC: Runs the population dynamics of *Sitophilus sp.* when the initial population, °C, %RH, and number of weeks are fed into the program.

INSINC2: A second estimate of population dynamics of *Sitophilus sp.* for an 'out-of-equilibrium' situation where the % moisture content is an input. From data of Evans (1982).

STAT: Properties of the normal curve, 'y' values, and area under the curve for a given number of standard deviations, 'x'.

STATP: A suggested way to transform % loss data into a normal distribution for reliable anaylsis of variance and then to reconvert the statistical parameters to actual loss.

SOL: Solves the parameters 'A' and 'B' in log-log curves such as P = B*(Q^A), the typical grains pressure resistance curve.

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AIRBAL

```
5  DIM T(20)
10 PRINT "MASS BALANCE BETWEEN AIR AND PADDY"
40 CLEAR
50 INPUT "TYPE, 'W-CHANGE' OR 'H-CHANGE' OR 'EXIT'"; S$
60 IF S$="W-CHANGE" THEN GOSUB 90 : GO TO 160
70 IF S$="H-CHANGE" THEN GOSUB 90 : GO TO 220
80 IF S$="EXIT" GO TO 280
90 INPUT "Q (m^3/time unit)"; Q
100 INPUT " V, Specific Volume (m^3/kg)"; V
110 INPUT "NO. OF TIMES FOR t" ; N
120 FOR I=1 TO N
130 PRINT " t "; : PRINT I; : INPUT T : T(I)=T
140 NEXT I
150 RETURN
160 INPUT "HUMIDITY RATIO IN AIR OUT, HO"; HO
170 INPUT "HUMIDITY RATIO IN AIR IN, HI" ; HI
180 FOR I=1 TO N
190 SUM=SUM+T(I)*(Q/V)*(HO-HI)
200 NEXT I
205 PRINT "WATER REMOVED FROM PADDY = "; SUM; "kg/tonne"
210 GO TO 40
220 INPUT "ENTHALPY IN AIR OUT" ; HO1
230 INPUT "ENTHALPY IN AIR IN" ; H2
240 FOR I=1 TO N
250 SUM=SUM+T(I)*(Q/V)*(HO1-H2)
260 NEXT I
265 PRINT "HEAT REMOVED FROM PADDY = " ;SUM; "kJ/tonne"
270 GO TO 40
280 END
```

AIRPAS

```
10 PRINT "PASCALS OF VAPOR PRESSURE AT SATURATION"
20 INPUT "TEMPERATURE, C°" ; CEN
30 T=CEN+273.16
40 X= -27405.526+(T*97.5413)-(.146244*T^2)+(.12558*10^(-3)*T^3)-
     (.48502*10^(-7)*T^4)
50 Y= (4.34903*T)-(.3938*10^(-2)*T^2)
60 PAS=EXP(X/Y+16.91134)
70 PRINT "SATURATION VAPOR PRESSURE = "; PAS
80 INPUT "ANY MORE DATA, (Y/N)"; A$
90 IF A$="Y" GO TO 20 : END
```

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AIRPOW

```
10 PRINT "GIVES kW OF AIR POWER"
15 PRINT "******************"
20 PRINT
30 INPUT "SPECIFIC VOLUME OF AIR , m^3/kg"; SVOL
40 INPUT "PASCALS OF TOTAL PRESSURE" ; P
50 INPUT "VOLUME OF AIR DELIVERY, m^3/min"; Q
60 PRINT
70 KW=(Q/SVOL/60)*(P*SVOL/9.80665)/102.2
80 PRINT "AIR POWER="; KW          "kW"
90 INPUT "ANY MORE DATA? (Y/N)"; A$
100 IF A$="Y" GOTO 30
110 END
```

AIRVEL

```
10 PRINT "VELOCITY OF AIR FOR A GIVEN VEL. PRESSURE AND SP. VOLUME"
15 PRINT "**********************************************"
20 PRINT
30 INPUT "SPECIFIC VOLUME OF THE AIR (m^3/kg)"; SVOL
40 INPUT "PASCALS OF VELOCITY PRESSURE" ; P
50 PRINT
55 B=9.80665/SVOL
60 V=(2*9.80665*P/B)^.5
70 PRINT "VELOCITY IN m/s = " ; V
80 PRINT
90 INPUT "ANY MORE DATA? (Y/N)" ; A$
100 IF A$="Y" GOTO 30
110 END
```

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AIRPSY

```
5 DIM A(9)
7 FOR I=0 TO 8 : READ A(I) : NEXT I
10 PRINT "PROPERTIES OF AIR"
20 INPUT "TEMPERATURE, C°"; CEN
25 INPUT "WET BULB TEMPERATURE, C°" ; CWB
30 TWB=CWB+273.16 : T=CEN+273.16
40 X=-27405.526+(T*97.5413)-(.146244*T^2)+(.12558*10^(-3)*T^3)-
     (.48502*10^(-7)*T^4)
50 Y=(4.34903*T)-(.3938*10^(-2)*T^2)
60 PAS=EXP(X/Y+16.91134)
70 PRINT "SATURATION VAPOR PRESSURE= "; PAS; "Pascals"
170 LHT= 2502535.259-(2385.76424*CEN)
180 PRINT "LATENT HEAT OF VAPORIZATION=" ; LHT; "J/kg"
190 HX=-27405.526+(97.5413*TWB)-(.146244*TWB^2)+
                  (.12558E-3*TWB^3)-(.48502E-7*TWB^4)
200 HY=(4.34903*TWB)-(.3938E-2*TWB^2)
210 PASWB=EXP(HX/HY+16.91134)
220 PRINT "VAPOR PRESSURE AT WET BULB SATURATION"; PASWB; "P"
230 LHTWB=2502535.259-(2385.76424*CWB)
240 PAV=500 : PATM=101325
260 BH=1006.9254*(PASWB-PATM)*(1+(.15577*PAV/PATM))
270 BG=.62194*LHTWB : B=BH/BG
280 PV2=PASWB-(B*(CWB-CEN))
290 IF PV2-PAV>50 THEN PAV=PAV+25 : GOTO 260
300 PRINT "VAPOR PRESSURE = " ; PAV; "P"
310 RH= PAV/PAS*100 : PRINT "% RELATIVE HUMIDITY=" ; RH
330 V= 287*T/(PATM-PAV) : PRINT "SPECIFIC VOLUME = "; V ; "m^3/kg"
350 HRAT=PAV*.6219/(PATM-PAV)
360 PRINT "HUMIDITY RATIO=" ; HRAT; "kg water/kg air"
390 DATA 19.5322,13.6626,1.17678,-.189693,.087453,-.0174053,
         .00214768,-.138343E-3,.383E-5
400 F=LOG(PAV*.00145)
410 FOR I=0 TO 8
420 S=F^I*A(I) : SUM=SUM+S : NEXT I
450 TAS=SUM-17.78
460 PRINT "DEW POINT TEMPERATURE="; TAS; "C°"
470 HAIR=1006.9254*CEN : HSW=4186.8*HRAT*TAS
```

```
490 HFG=(2502535.259-(2385.76424*TAS))*HRAT
500 HSV=1875.6864*HRAT*(CEN-TAS) : ENT=HAIR+HSW+HFG+HSV
510 PRINT "ENTHALPY = " ; ENT; "J/kg dry air"
530 DI=(RH-65)*PAS*10^(-4) : PRINT "DETERIORATION INDEX =" ; DI
550 INPUT "ANY MORE DATA? (Y/N)" ; A$
560 IF A$="Y" GOTO 20
```

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DMLEMCDI

```
10 PRINT "% DML/DAY OF PADDY IN EQUILIBRIUM WITH DI"
20 PRINT : INPUT "DETERIORATION INDEX"; DI : PRINT "DI="; DI
30 IF DI>=12 THEN A=.82 : B=13.16 : GOTO 100
40 IF DI>=5 THEN A=.486 : B=9.149 : GOTO 100
50 IF DI>=2.78 THEN A=.369 : B=8.567 : GOTO 100
60 IF DI<0 THEN GOTO 20 ELSE A=.151 : B=7.96 : GOTO 100
100 P=EXP(A*DI-B) : PRINT "% DML/DAY =" ; P
110 INPUT "ANY MORE DATA? (Y/N); A$
120 IF A$="Y" GOTO 20 : END
```

DMLFAO

```
10 PRINT "%DML/DAY FOR PADDY, LOONZAIN OR RICE"
20 INPUT "TYPE OF GRAIN, PD, LZ, OR R"; G$
30 INPUT "MOISTURE CONTENT, % wb" ; M
40 IF M>17 THEN PRINT "VALID ONLY FOR 17>M>10" : GOTO 30
50 IF G$="PD" GOTO 100
52 IF G$="LZ" GOTO 110
54 IF G$="R" GOTO 120 ELSE GOTO 20
60 D=.68*(10^(A*M-B))
70 PRINT "%DML/DAY = " ; D
80 INPUT "ANY MORE DATA? (Y/N)" ; A$
90 IF A$="Y" GOTO 20 : END
100 IF M>13.2 THEN A=.44 : B=9.08
102 IF M<=13.2 THEN A=.21 : B=6.04
105 GOTO 60
110 IF M>13.7 THEN A=.44 : B=9.41
112 IF M<=13.7 THEN A=.17 : B=5.67
115 GOTO 60
120 IF M>14.1 THEN A=.49 : B=10.48
122 IF M<=14.1 THEN A=.16 : B=5.83
125 GOTO 60
```

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DMLKSU

```
10 PRINT "%DML FOR LONG OR MED. GR. PADDY, KSU EQUATION"
20 INPUT "TYPE OF GRAIN, LONG (L) OR MEDIUM (M)"; G$
30 IF G$="L" GOTO 50
40 A=.000914 : C=.654 : D=.03756 : E=33.61 : GOTO 60
50 A=.001889 : C=.7101 : D=.0274 : E=31.63
60 INPUT "TEMPERATURE, C°"; CE
70 T=CE*1.8+32
80 INPUT "MOISTURE CONTENT, %wb"; M
90 W=M/100
100 INPUT "STORAGE TIME, DAYS"; DAYS
110 ST=DAYS*24/1000
120 X=A*ST^C : Y=EXP(D*(T-60)) : Z=EXP(E*(W-.14))
130 DML=100*(1-(EXP(-X*Y*Z)))
140 PRINT "% DRY MATTER LOSS = "; DML
150 INPUT "ANY MORE DATA? (Y/N)"; A$
160 IF A$="Y" GOTO 20 : END
```

DMLHRS

```
10 PRINT "DAYS FOR LONG OR MED. GRAIN PADDY TO LOSE A GIVEN %DM"
20 INPUT "TYPE OF GRAIN, LONG (L) OR MEDIUM (M)" ; G$
30 IF G$="L" GOTO 50
40 A=.000914 : C=.654 : D=.03756 : E=33.61 : GOTO 60
50 A=.001889 : C=.7101 : D=.0274 : E=31.63
60 INPUT "TEMPERATURE, C°"; CE : T=1.8*CE+32
70 INPUT "% MOISTURE CONTENT, w.b."; M : W=M/100
80 INPUT "% DRY MATTER LOSS"; ML : DML=ML/100
90 X=LOG(1-DML) : Y=EXP((T-60)*D) : Z=EXP((W-.14)*E)
100 ST=(-X/(A*Y*Z))^(1/C)
110 DAYS=ST*1000/24
120 PRINT "ALLOWABLE DAYS OF STORAGE ="; DAYS
130 INPUT "ANY MORE DATA? (Y/N)"; A$
140 IF A$="Y" GOTO 20
150 END
```

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ECOPL

```
10 INPUT "SELECT THE LOSS PROG. : VALUE (V), %DAM. K. (DK), GERMIN-
   ATION (G) OR EXIT (E)" ; L$
20 IF L$="V" GOTO 100
22 IF L$="DK" GOTO 200
24 IF L$="G" GOTO 300
30 IF L$="E" GOTO 440
100 INPUT "DAYS AFTER 2000 HOURS ON REAPING DAY" ; D
110 INPUT "% MOISTURE CONTENT > 15%, w.b." ; M
120 S=(M-15)^.69 : T=D^.35 : V=100-(3.51*S*T)
130 PRINT "PERCENT VALUE =" ; V
140 INPUT "ANY MORE DATA? (Y/N)"; A$
150 IF A$="Y" GOTO 100 ELSE GOTO 10
200 INPUT "MOISTURE CONTENT, %M=> 16" ; MC
210 D=EXP((MC-16)*.29)-1
220 PRINT "VISIBLY DAMAGED PADDY KERNELS AFTER 10 DAYS =" ; D
230 INPUT "ANY MORE DATA? (Y/N)"; B$
240 IF B$="Y" GOTO 200 ELSE GOTO 10
300 INPUT "INITIAL GERMINATION, %" ; GI
310 INPUT "% MOISTURE CONTENT" ; CM
320 INPUT "TEMPERATURE, C°"; TE
330 A=.069*TE : B=.159*CM : K=10^(5.686-A-B)
340 PRINT "WEEKS TO LOSE 50% GERMINATION =" ; K
350 INPUT "WEEK AT WHICH GERMINATION DESIRED" ; W
360 R=W/K
362 IF R<1 THEN GOTO 400
370 G=GI*(1-(GW/100))
380 PRINT "GERMINATION AT 'W' WEEKS IS" ; G
385 INPUT "ANY MORE DATA? (Y/N)" ; C$
390 IF C$="Y" GOTO 300 ELSE GOTO 10
400 GW=7.8*(EXP(R*2)-1)
410 GOTO 370
420 GW=100-(7.8*((EXP((2-R)*2))-1))
430 GOTO 370
435 GW=100
437 GOTO 370
440 END
```

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ECORBLD

```
10 PRINT "ESTIMATE OF VALUE OF RICE BLENDS"
30 INPUT "MILLED RICE CONTENT, %= H, LB, SB" ; MH, MB, MS
40 INPUT "SALE GRADE, %= H, LB, SB" ; EH,EB,ES
50 REM "PRICE VALUE CONSTANTS FOR RICE SALE ARE"
60 HP=3 : BP=2.4 : SP=1.32
70 HD=10*(MH-EH) : BR=10*(MB-EB) : SB=10*(MS-ES)
80 INPUT "MILLED RICE VALUE" ; MP
90 INPUT "BLENDED RICE VALUE"; EP
100 COST=MP-((HD*HP)+(BR*BP)+(SB*SP))
110 PROF=EP-COST
120 PRINT "RELATIVE PROFIT" ; PROF
130 INPUT "ANY MORE DATA? (Y/N)" ; R$
140 IF R$="Y" GOTO 30 : END
```

ECOWT

```
10 PRINT "WEIGHT OF DRIED GRAIN"
30 INPUT "ORIGINAL WEIGHT IN kg" ; KG
40 INPUT "ORIGINAL % MOISTURE" ; MO
50 INPUT "FINAL % MOISTURE" ; M
60 DM=((100-MO)/100)*KG : DWT=DM/(100-M)*100
70 PRINT "DRIED WEIGHT=" ; DWT; "kg"
80 INPUT "ANY MORE DATA? (Y/N)" ; A$
90 IF A$="Y" GOTO 30 : END
```

GRDK

```
10 PRINT "% DAMAGED PADDY KERNELS IN 10 DAYS"
20 INPUT "% MOISTURE CONTENT" ; M
30 IF M<=16 GOTO 45
40 DK=EXP((M-16)*.29)-1 : GOTO 50
45 DK=0
50 PRINT "% INCREASE IN DAMAGED KERNELS IN 10 DAYS" ; DK
60 INPUT "ANY MORE DATA? (Y/N)" ; A$
70 IF A$="Y" GOTO 20  : END
```

GRVAL

```
10  PRINT "ESTIMATE OF PADDY VALUE HELD SEVERAL DAYS"
20  INPUT "DAYS AFTER 2000 HOURS ON DAY OF HARVEST" ; D
30  INPUT "MOISTURE CONTENT, %" ; M
40  IF M<=15 THEN PRINT "VALUE IS 100%" : GOTO 70
50  W=100-(3.51*(D^.35)*((M-15)^.69))
60  PRINT "PADDY VALUE IS NOW" ; W
70  INPUT "ANY MORE DATA? (Y/N)" ; A$
80  IF A$="Y" GOTO 20  : END
```

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ECOTCOST

```
10  INPUT "TRANSPORT COSTS FOR PADDY (P) OR RICE (R)?" ; C$
20  REM "METHODS ARE 1(HAND), 2(OX CRT), 3(TR PAVING), 4(TR GRAV),
    5(TR DIRT), 6(TR BAD RD), 7(BOAT)" : SUM=0
30  IF C$="R" GOTO 300
40  INPUT "METHOD, DISTANCE, km = M,KM" ; M,KM
50  IF M=1 THEN SUM=SUM+(.839*KM) : GOTO 200
60  IF M=2 THEN SUM=SUM+(.325*KM) : GOTO 200
70  IF M=3 THEN GOTO 120
80  IF M=4 THEN GOTO  140
90  IF M=5 THEN GOTO  160
100 IF M=6 THEN GOTO  180
110 IF M=7 THEN SUM=SUM+(1.02+(KM^.45*.568)) : GOTO 200
120 IF KM>=32.2 THEN SUM=SUM+(.33+KM*.086)  : GOTO 200
130 SUM=SUM+(.33+KM*.099) : GOTO 200
140 IF KM>=32.2 THEN SUM=SUM+(.4+KM*.106) : GOTO 200
150 SUM=SUM+(.4+KM*.116) : GOTO 200
160 IF KM>=32.2 THEN SUM=SUM+(.4+KM*.115) : GOTO 200
170 SUM=SUM+(.4+KM*.132) : GOTO 200
180 IF KM>=32.2 THEN SUM=SUM+(.46+KM*.165) : GOTO 200
190 SUM=SUM+(.46+KM*.198)
200 INPUT "ANY MORE DATA? (Y/N)" ; D$
210 IF D$="Y" GOTO 40
220 PS=100-SUM
230 PRINT "PRICE SURFACE (% VALUE) OF PADDY=" ; PS : END
300 INPUT "METHOD AND DISTANCE (M,KM) FOR RICE" ; M,KM
310 IF M=1 THEN SUM=SUM+(.325*KM) : GOTO 460
320 IF M=2 THEN SUM=SUM+(.134*KM) : GOTO 460
330 IF M=3 THEN GOTO 380
340 IF M=4 THEN GOTO 400
350 IF M=5 THEN GOTO 420
360 IF M=6 THEN GOTO 440
370 IF M=7 THEN SUM=SUM+(.347+KM*.00616) : GOTO 460
380 IF KM>=32.2 THEN SUM=SUM+(.15+KM*.033) : GOTO 460
390 SUM= SUM+(.15+KM*.040) : GOTO 460
400 IF KM>=32.2 THEN SUM=SUM+(.13+KM*.040) : GOTO 460
410 SUM= SUM+(.13+KM*.046) : GOTO 460
420 IF KM>=32.2 THEN SUM=SUM+(.19+KM*.046) : GOTO 460
430 SUM=SUM+(.19+KM*.053) : GOTO 460
440 IF KM>=32.2 THEN SUM=SUM+(.21+KM*.066) : GOTO 460
450 SUM=SUM+(.21+KM*.080)
460 INPUT "ANY MORE DATA? (Y/N)" ; R$
470 IF R$="Y" GOTO 300
480 PR=100-SUM
```

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GRAER

```
10  PRINT "AERATION RATE FOR MAIZE OR PADDY"
20  PRINT
30  INPUT "MOISTURE CONTENT, %" ; M
40  INPUT "TYPE OF GRAIN, PADDY (P) OR MAIZE (MA)" ; A$
50  IF A$="P" THEN GOSUB 230
60  IF A$="MA" THEN GOSUB 320 ELSE GOTO 30
230 PRINT "AERATION RATE (m^3/tonne minute) FOR PADDY"
240 A=.44 : B=6.08
250 GOSUB 420
260 END
320 PRINT "AERATION RATE (m^3/tonne minute) FOR MAIZE"
330 A=.27 : B=3.33
340 GOSUB 420
350 END
420 X=10^((M*A)-B))/1.721
505 INPUT "HRS/DAY OR AV. DAILY RH KNOWN? (HD/ACRH)" ; RH$
506 IF RH$="ACRH" GOSUB 600
507 INPUT "HRS/DAY OF FAN OPERATION=" ; HRS
510 Q=X/HRS
520 PRINT "q=" ; Q ; "m^3/tonne minute"
530 RETURN
600 INPUT "AVERAGE DAILY RELATIVE HUMIDITY (24 hrs.)" ; ACRH
610 A=100-ACRH : HRS=0
615 INPUT "ALLOWABLE RH OF AERATION AIR" ; GRH
620 FOR I = 1 TO 48
630 Y=A*SIN(.1309*I)
640 RH=ACRH+Y
650 IF RH<GRH THEN HRS=HRS+.5
660 NEXT I
670 RETURN
```

GRSPR

```
10  PRINT "RESISTANCE OF PADDY TO AIR FLOW"
20  PRINT
30  INPUT "DEPTH OF PADDY, m" ; D
40  INPUT "AERATION RATE, m^3/tonne min." ; Q
50  V=.58*Q*D
60  P=V^1.32*D*53.7
70  PRINT "PASCALS OF PRESSURE=" ; P
80  INPUT "ANY MORE DATA? (Y/N)", A$
90  IF A$="Y" GOTO 30
100 END
```

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GRSPR2

```
5   PRINT "RESISTANCE OF BROWN RICE OR MILLED RICE TO AIR FLOW"
10  INPUT "BROWN RICE (BR) OR MILLED RICE (MR)" ; A$
20  IF A$="BR" GOTO 100
30  A=1.08 : B=8.507 : C=1.161 : D=8.679
40  INPUT "AIR FLOW (m^3/s per m^2 of floor)" ; Q
50  IF Q>.04 GOTO 70
60  P=EXP(A*LOG(Q)+B) : GOTO 80
70  P=EXP(C*LOG(Q)+D)
80  PRINT "PASCALS PER m OF DEPTH" ; P
90  END
100 A=1.079 : B=8.5806 : C=1.122 : D=8.717
110 GOTO 40
```

GRDEPTH

```
10  PRINT "DEPTH OF PADDY ALLOWABLE"
20  INPUT "PASCALS OF STATIC PRESSURE=" ; P
30  INPUT "AERATION RATE, m^3/tonne min." ; Q
40  A=Q^(-.565) : B=P^.431 : D=.245*A*B
50  PRINT "METERS OF DEPTH ALLOWABLE=" ; D
60  INPUT "ANY MORE DATA? (Y/N)" ; A$
70  IF A$="Y" GOTO 20  : END
```

SOL

```
10  PRINT "FOR WRITING EQUATIONS FOR GRAINS RESISTANCE"
20  PRINT "THIS SOLVES FOR A AND B IN LN(P)=A*LN(Q)+B"
30  PRINT
40  INPUT "X VALUES FOR X1,X2" ; W,X
50  INPUT "Y VALUES FOR Y1,Y2" ; Y,Z
60  X1=LOG(W) : X2=LOG(X) : Y1=LOG(Y) : Y2=LOG(Z)
70  A=(X2-X1)/(Y2-Y1)
80  B= -A*Y1+X1
90  PRINT "A AND B = " ; A  "and" ; B
100 INPUT "ANY MOR DATA? (Y/N)" ; A$
110 IF A$="Y" GOTO 40
120 END
```

GRGER

Note: For obtaining the estimated viability of paddy in storage, use the ECOPL program.

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GREMC

```
10 PRINT "CHUNG-PFOST EQUILIBRIUM MOISTURE FOR GRAINS"
20 PRINT "****************************************"
30 PRINT "Codes for grains are: Barley=BA, Beans=BE, Maize=MA, Ground"
40 PRINT "nuts in the pod=GN, Peanuts shelled=GS, Paddy=P, Sorghum=SOR"
50 PRINT "Soyabeans=SB, Durham wheat=DW, Hard wheat=HW, S. wh.= SW"
60 INPUT "CODE FOR THE SELECTED GRAIN" ; A$
70 IF A$="BA" GOTO 140
75 IF A$="BE" GOTO 150
80 IF A$="MA" GOTO 160
85 IF A$="GN" GOTO 180
90 IF A$="GS" GOTO 170
95 IF A$="P" GOTO 190
100 IF A$="SOR" GOTO 200
105 IF A$="SB" GOTO 210
110 IF A$="DW" GOTO 220
120 IF A$="HW" GOTO 230
130 IF A$="SW" GOTO 240
140 A=761.66 : B=19.889 : C=91.323 : E=.33363 : F=.050279 : GOTO 250
150 A=962.58 : B=15.975 : C=160.629 : E=.43001 : F=.062596 : GOTO 250
160 A=312.30  : B=16.958 : C=30.205 : E=.33872 : F=.058970 : GOTO 250
170 A=254.90 : B=29.243 : C=33.892 : E=.18948 : F=.034196 : GOTO 250
180 A=522.01 : B=37.903 : C=12.345 : E=.16510 : F=.026383 : GOTO 250
190 A=594.61 : B=21.732 : C=35.703 : E=.29394 : F=.046015 : GOTO 250
200 A=1099.67 : B=19.644 : C=102.849 : E=.35649 : F=.050907 : GOTO 250
210 A=328.3   : B=13.917 : C=100.288 : E=.41631 : F=.071853 : GOTO 250
220 A=921.65 : B=18.077 : C=112.35 : E=.37761 : F=.055318 : GOTO 250
230 A=529.43 : B=17.609 : C=50.998 : E=.35616 : F=.056788 : GOTO 250
240 A=726.49 : B=23.607 : C=35.662 : E=.27908 : F=.042360 : GOTO 250
250 INPUT "IS ENTRY IN %MC OR %RH? (MC/RH)" ; B$
260 IF B$="MC" GOTO 360
270 INPUT "RELATIVE HUMIDITY, %" ; RH
280 RH=RH/100 : Z=LOG(RH)
290 INPUT "TEMPERATURE,C°"; T
300 M=(E-(F*LOG((-1)*(T+C)*Z)))  : MC=100*(M/(1+M)
310 PRINT "THE WET BASIS  % MOISTURE CONTENT=" ; MC
320 INPUT "ANY MORE DATA? (Y/N)" ; C$
330 IF C$="Y" GOTO 20 : END
360 INPUT "MOISTURE CONTENT, % WET BASIS" ; MC
370 INPUT "TEMPERATURE, C°" ; T
380 M=MC/(100-MC) : WE=EXP(-1)*B*M) : R=EXP(WE*(-1)*A/(T+C))
390 RH=R*100
400 PRINT "THE % EQUILIBRIUM RH=" ; RH
410 INPUT "ANY MORE DATA? (Y/N)" ; D$
420 IF D$="Y" GOTO 20 : END
```

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INSINC

```
10 PRINT "ESTIMATES SITOPHILUS POPULATION"
20 INPUT "INITIAL SIT. POPULATION" ; PO
30 INPUT "DETERIORATION INDEX OF CLIMATE" ; DI
40 REM "THE MAX. 28 DAY RATE OF INCREASE IS TAKEN AS 15"
50 R=15 : X=(2.9-DI)/3.3 : Y=.399*EXP(-X^2/2) : RI=R*Y/.399
60 RM=LOG(RI)/4
70 INPUT "WEEKS AFTER INITIAL POP. INPUT, W" ; W
80 IF W>22 THEN 250
90 IF W>11 THEN 200
100 PF=PO*EXP(RM*W)
110 PRINT "POPULATION AT 'W' WEEKS =" ; PF
120 INPUT "ANY MORE DATA? (Y/N)" ; A$
130 IF A$="Y" GOTO 20 : END
200 PF=(2*PO*EXP(RM*11))-(PO*EXP(RM*(22-W))) : GOTO 110
250 PF=2*PO*EXP(RM*11) : GOTO 110
```

INSINC2

```
10 PRINT "ALTERNATE SITOPHILUS POPULATION MODEL"
20 INPUT "INITIAL POPULATION, PO" ; PO
30 INPUT "VAPOR PRESSURE OF AIR, Pascals" ; VP
40 INPUT "MOISTURE CONTENT OF GRAIN" ; MC
50 A=(0.0794*MC^2)-(2.509*MC)+21.81  : A=A/1000
60 Z=3.18-(A*(VP-400))
70 B=.195+1.485*Z
80 C=(EXP(B)+EXP(-B))/2 : T=4.8*C
85 PRINT "ESTIMATED WEEKS FOR 1 GENERATION" ; T
90 Y=.399/(EXP(Z^2/2))
100 R=15*Y/.399
110 RM=LOG(R)/4
120 INPUT "WEEKS FOR THE FINAL POPULATION, W"; W
130 IF W>4*T THEN GOTO 200
140 IF W>2*T THEN GOTO 220
150 PF=PO*EXP(RM*W)
160 PRINT "POPULATION ESTIMATE AT 'W' WEEKS" ; PF
170 INPUT "ANY MORE DATA? (Y/N)"; A$
180 IF A$="Y" GOTO 20
190 END
200 PF=2*PO*EXP(RM*2*T) : GOTO 160
220 PF=(2*PO*EXP(RM*2*T))-(PO*EXP(RM*(4*T-W))) : GOTO 160
```

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STAT

```
10 PRINT "GIVES ORDINATE AND AREA UNDER NORMAL CURVE"
20 INPUT " STANDARD DEVIATION FROM THE MEAN, S" ; S
30 Y=EXP(-S^2/2)/SQR(6.283185) : SUM=0.0
40 PRINT "THE ORDINATE OF THE NORMAL CURVE =" ; Y
50 T=1/(1+.2316419*S) : DIM A(5)
70 A(1)=.319381530 : A(2)=-.356563782 : A(3)=1.781477937
80 A(4)=-1.821255978 : A(5)=1.330274429
100 FOR I = 1 TO 5
110 TERM=A(I)*T^I : SUM=SUM+TERM
120 NEXT I
130 P=Y*SUM : Q=1-P
140 PRINT "AREA UNDER THE CURVE TO 'S' AND BEYOND =" ; Q     ; P : END
```

STATP

```
10 PRINT "ANOV OF PH LOSS DATA BY CONVERSION AND RECONVERSION"
30 INPUT "STUDY 1 OR STUDY 2 (1/2)" ; ST
40 DIM A(25)
50 INPUT "MODAL % LOSS"; MO
60 FOR I = 1 TO 20 : READ A(I) : NEXT I
70 IF ST=1 THEN DA=1 : N=10 ELSE DA11 : N=20
80 STL=0.0  : STR=0.0  : STLS=0.0  : STRS=0.0
90 FOR I=DA TO N
100 IF A(I)>MO GOTO 170
110 X=(A(I)/MO)  : Y=ATN(X/SQR(1-X*X))
120 TLL=.5*63.662*Y : STL=STL+TLL  : STLS=STLS+TLL^2 : GOTO210
170 P=1-((A(I)-MO)/(100-MO))  : Q=(100-MO)/MO  : Z=(P^Q)
180 W=ATN(Z/SQR(1-Z*Z))  : TLR=100-(.5*W*63.662)
190 STR=STR+TLR  : STRS=STRS+TLR^2
210 NEXT I
220 DATA 4.6,8.2,6.3,7.1,5.4,4.0,10.5,5.0,18.0,2.9
230 DATA 6.1,18.0,14.2,8.9,12.1,15.3,11.6,13.7,14.8,24.3
240 SS=STRS+STLS  : S=STL+STR : M=S/10
250 SD=SQR((SS-2*S*M+10*M^2)/(10-1))
260 PRINT "STANDARD DEVIATION OF TRANSFORMED DATA ="; SD
270 A=50-SD  : L=SIN(A*2/63.662)*MO
280 PRINT "STND. DEVIATION OF %PHL TO LEFT="; L
290 B=50+SD  : C=(100-MO)/MO  : D=(100-MO)^C
300 LR=100-((D*SIN(2*(100-B)/63.662))^(1/C))
310 PRINT "STND. DEVIATION OF %PHL TO RIGHT="; LR
320 B=2.3625/(LOG(LR)-LOG(L))  : A=-.1732/L^B
330 PRINT "CONSTANTS A & B IN P=>EXP(A*L^B) ARE"; A     "AND"; B
```

Design of Air Distribution Systems and Fan Selection for Grain Aeration

A.J. Hunter*

Abstract

Bulk seed is frequently aerated for the purpose of drying and cooling. Some simple formulae are presented to assist the designer of an aeration system with regard to: the control system, the selection of an airflow-rate, the air distribution system, and the selection of a suitable fan. Some two-dimensional airflow patterns are shown for aeration of stores having flat floors and vertical sides, and also for crossflow in circular, cylindrical stores.

ALL deterioration mechanisms in seeds depend on moisture content, temperature, and time, and since equilibrium wet bulb temperature increases with grain moisture content and grain dry bulb temperature, a useful indicator of the likely deterioration is the wet bulb temperature–time integral for the seedbulk. A suitable objective of an ambient aeration system is therefore to reduce the wet bulb temperature time integral accumulated during the storage period.

The essential characteristics of a good seedbulk aeration system are:

1. to make best use of the available air,
2. to treat the seedbulk as uniformly as possible,
3. to require as little maintenance as possible,
4. to require as little operator attention as possible,
5. to minimise uptake of moisture,
6. to have the least cost.

There are three identifiable features of seedbulk aeration systems. They are:

1. the fan,
2. the air distribution system,
3. the fan control system.

In practice, all three features vary widely over the range of possibilities in response to wide ranges of store geometry, climate, and seed type. Variations also arise from factors such as availability of electric power and construction materials. Airflow may be either upward or downward; more specifically we may refer to a blowing system or a suction system.

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Because of the temperature rise experienced by the air as it passes through the fan, a suction system will achieve a lower seedbulk temperature than an equivalent blowing system. Against this, the relative humidity and hence the moisture-content of the wetting front will be less in the case of the blowing system (Sutherland et al. 1971). The suction system also involves reduced air pressure inside the store and so there may be ingress of liquid water if the store is not properly sealed. There is no significant difference in cost between suction and blowing aeration systems.

The Hygroscopic Nature of Seeds

Because seeds are hygroscopic, the driving potential for cooling is the wet bulb temperature of the aerating air. It is reasonable to refer to the wet bulb temperature of the seedbulk, which is the wet bulb temperature of the interstitial air when equilibrium is reached.

In the following discussion, I shall refer to the wet bulb temperature of either the seedbulk or the air as simply 'temperature'.

Control System for Aeration Fan

The time-proportioning controller developed by CSIRO Australia (Elder 1972) takes advantage of the lowest ambient temperatures. It is an electronic device which automatically runs the fan for a preset fraction of time. This fraction 'F' is at the discretion of the designer. Seed is usually harvested and introduced to the store at above average ambient temperature; it is usual therefore to set F equal to unity initially, and reduce it when the seedbulk temperature reaches the upper extreme of the aerating temperature. In fact, it may be shown (Hunter 1985a) from an approximate analysis that for a suction system, the optimum value of F is given by

$$F = 1 \qquad \{b < \bar{t}\}$$

$$F = \frac{\bar{t} - a}{b - a}, \qquad \{a < \bar{t} < b\} \qquad (1)$$

$$\text{and} \quad F = O, \qquad \{a > \bar{t}\}$$

a and b correspond to $\bar{t}_a - s\sqrt{3}$ and $\bar{t}_a + s\sqrt{3}$, respectively, where $\bar{t}_a$ is the mean and s the standard deviation of ambient temperature, and $\bar{t}$ is the average seedbulk temperature.

For a blowing system the fraction is slightly less, to account for the penalty of the temperature rise in the fan.

Airflow Rate

For a blowing system there is an optimum thermodynamic airflow rate because of the trade off between fan temperature rise and rate of cooling. For a suction system there is no optimum airflow rate; the greater the airflow rate the greater the rate of cooling.

It is reasonable to suggest that the best airflow rate to use will be determined by the initial cooling stage: this is when the seedbulk is hottest and the need for cooling is greatest.

It is instructive for the purposes of deciding what airflow rate to use to consider the simple model where for the purposes of the initial cooling, F is taken as unity, and the initial average seedbulk temperature $\bar{t}_0$ is higher than the average ambient temperature $\bar{t}_a$.

If q is the specific airflow rate in say $m^3/kg\ s$ then, neglecting heat conduction across the boundary of the seedbulk, it may be shown that (Hunter 1985a) the normalised seedbulk temperature is

$$\Xi_i = \frac{\bar{t} - \bar{t}_a}{\bar{t}_0 - \bar{t}_a} = e^{-\rho_s \Gamma q \theta}. \qquad (2)$$

θ is time, ρ_s the density of the seedbulk, and Γ is the ratio of the speed of a temperature or moisture front to the face velocity of the aerating air. For a temperature front, Γ may be approximated by

$$\Gamma = \zeta/1000$$

$$\text{where} \quad \zeta = \frac{\partial t_{ad}}{\partial t_a} \,|\, w. \qquad (3)$$

Integrating (2) over a storage period τ we find the normalised temperature time integral Ω to be given by

$$\Omega = \frac{1}{\rho_s \Gamma q \tau}[1 - e^{-\rho_s \Gamma q \tau}]. \qquad (4)$$

Equations (2) and (4) are graphed in Figure 1. By putting values on storage periods of interest, and on the specific airflow rate q, one can see immediately how much benefit, by way of reduction in temperature–time integral will have been achieved. In Australia, we use q values of around 1 *l*/st or 10^{-6} m^3/s kg. It turns out that the storage period in such a case is given approximately by the abscissa scale in Figure 1 in the units of weeks.

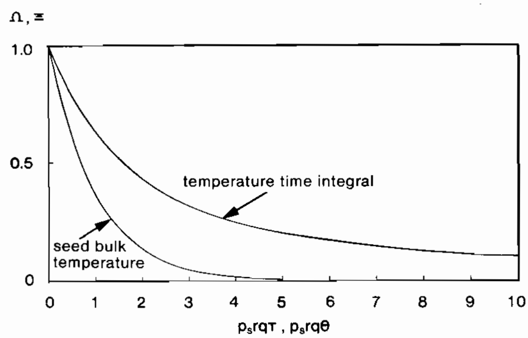

Fig. 1. Normalised seedbulk temperature Ξ_i and normalised temperature-time-integral Ω graphed as a function of the dimensionless time parameters, $\rho_s \Gamma q \Theta$ and $\rho_s \Gamma q \tau$, respectively.

Uniformity of Aeration between Ducts

To ensure uniformity of aeration between ducts, the criterion suggested by Holman (1960) is recommended. Holman states that the ratio of the longest path to the shortest path between the duct and the seedbulk surface should not exceed 1.5. For a level-loaded, flat-floored store, this means a spacing between ducts no greater than the depth of the seedbulk.

Uniformity of Aeration along a Duct

The variation of static pressure along an aeration duct gives a good indication of the variation of aeration flow rate along the duct length. The static pressure variation along a duct is affected by friction losses and by static pressure regain (Hunter 1985b). (Static pressure regain is the increase in static pressure resulting from a loss of kinetic energy in the air moving along the duct.) These effects are indicated in Figures 2 and 3 for suction and blowing aeration systems, respectively.

To overcome static pressure regain problems the duct should satisfy the condition

$$\frac{A}{X} > \frac{\sqrt{\rho_s \rho_a q}}{2R\sigma} \qquad (5)$$

A is the cross-sectional area of the duct, X is the plan area of the seedbulk served by the duct, ρ_s and ρ_a are the densities of the seedbulk and of the aerating air, q is the specific airflow rate, σ is the fractional variation of static pressure along the duct, and R is the first Ergun coefficient for the seed defined by

$$\frac{dp}{dx} = Rv + Sv^2. \qquad (6)$$

p is static pressure of air, x the distance coordinate, v the face velocity of the air, and R and S are constant coefficients for a particular seed type.

Equation (5) may be derived by setting the maximum velocity pressure in the duct equal to the fraction σ of the static pressure difference across the seed-bulk.

To prevent static pressure problems arising from friction in the duct take

$$l < \frac{12A}{P_w f} \qquad (7)$$

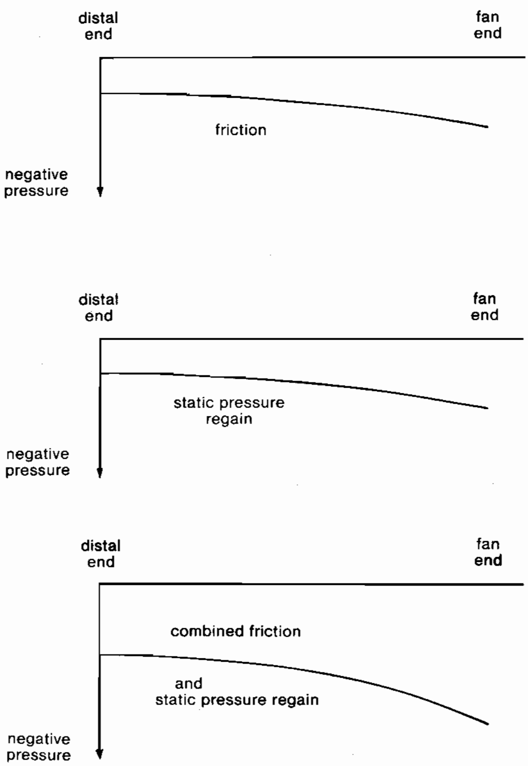

Fig. 2. The effect of friction and of static pressure regain on the distribution of static pressure of air along a duct for a suction aeration system.

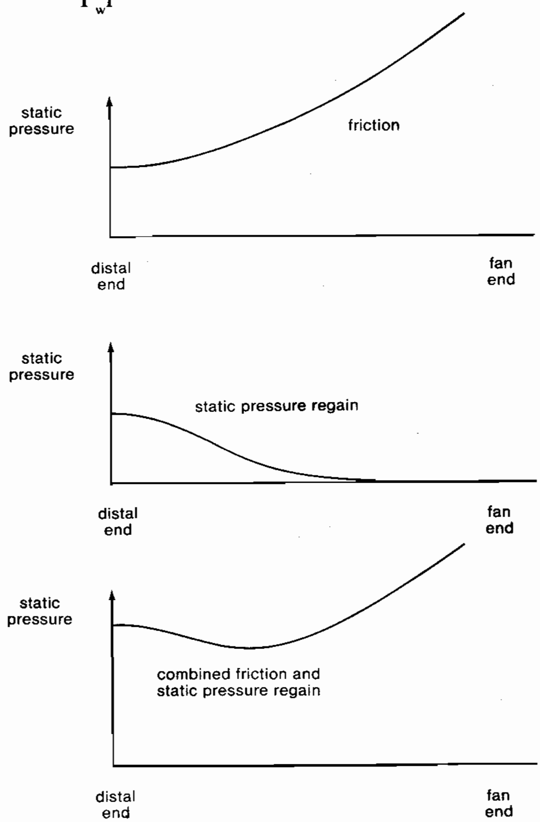

Fig. 3. The effect of friction and of static pressure regain on the distribution of static pressure of air along a duct for a blowing aeration system.

where P_w is the wetted perimeter of the duct and f is the D'arcy-Weisbach friction factor, which may be approximated for straight aeration ducts by

$$f = \frac{1.326}{\left(ln\frac{14.88A}{P_w\varepsilon}\right)^2} \quad (8)$$

The equivalent sand roughness height for the inner surface of the duct is ε.

Equation (7) is derived by considering friction losses alone, and then combining the result with (6).

Static pressure variation can be avoided by designing in accordance with equations (6) and (7).

Airflow Patterns in Aerated Seedbulks

Some airflow patterns for various two-dimensional duct and store geometries were derived using conformal mapping (Hunter 1983), and are shown in Figures, 4, 5, 6, 7, 8, and 9. The flowlines shown divide the airflow into 10 equal parts.

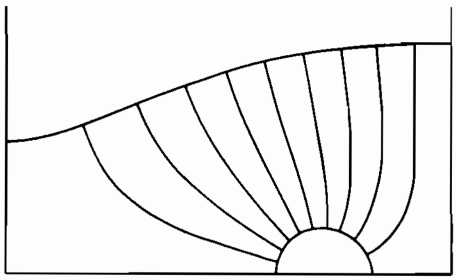

Fig. 4. Flow field approximating aeration of a seedbulk with a flat floor and vertical sides, using a half round duct.

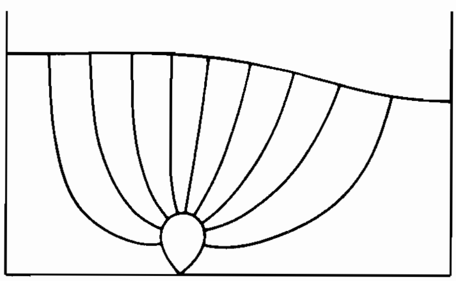

Fig. 5. Flow field approximating aeration of a seedbulk with a flat floor and vertical sides, using a round duct.

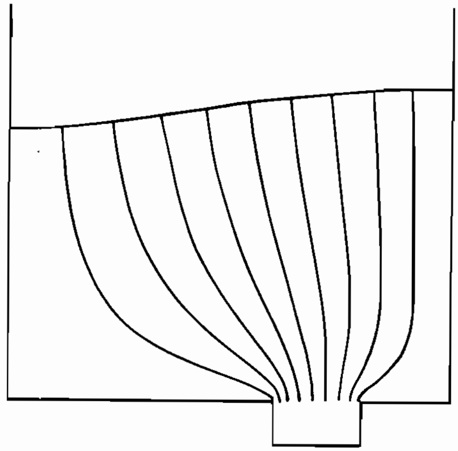

Fig. 6. Flow field approximating aeration of a seedbulk with a flat floor and vertical sides, using a perforated floor duct.

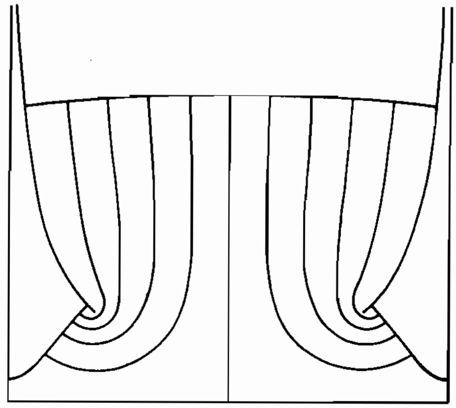

Fig. 7. Flow field approximating aeration of a seedbulk with a flat floor and vertical sides, using a symmetrical pair of louvre ducts.

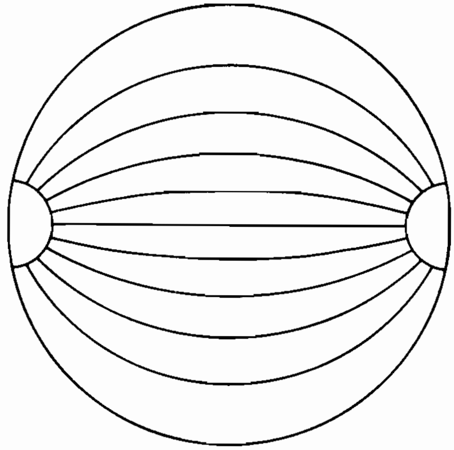

Fig. 8. Flow field approximating crossflow aeration of a circular cylindrical silo, using half round ducts.

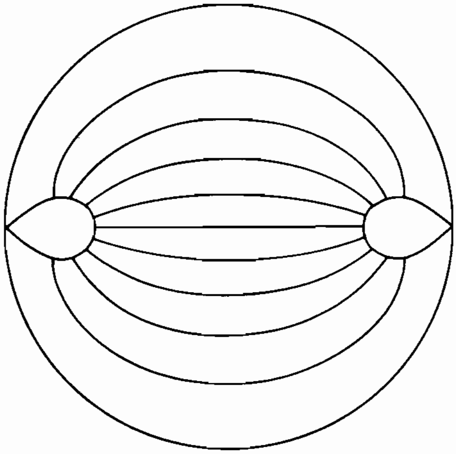

Fig. 9. Flow field approximating crossflow aeration of a circular cylindrical silo, using round ducts.

Estimation of Pressure Difference across an Aerated Seedbulk

The pressure difference across an aerated seedbulk may be estimated from the laminar flow term (linear) and the turbulent flow term (square) in the Ergun equation, (6).

For a floor-mounted duct system the linear term pressure difference may be estimated from

$$\Delta p_1 = \frac{RQ}{X}(H + \Delta H) \qquad (9)$$

where $\Delta H = \frac{W}{\pi} \, ln \, \frac{W}{2P_p}$

Two square law terms arise from the field close to the duct and from the field remote from the duct. They are

$$\Delta p_2 = \frac{SQ^2}{\pi l^2 P_p} \qquad (10)$$

and $$\Delta p_3 = \frac{SQ^2 H}{x^2} \qquad (11)$$

respectively.

For a crossflow aeration system in a circular cylindrical store of diameter D having semicircular ducts of radius r, we have

$$\Delta p_1 = \frac{2QR}{\pi l} \, ln \, (\frac{D}{r} - 1) \qquad (12)$$

$$\Delta p_2 = \frac{2SQ^2}{\pi l^2 P_p} \qquad (13)$$

and $$\Delta p_3 = \frac{SQ^2}{l^2 D}. \qquad (14)$$

The total pressure difference in each case is given by

$$\Delta p = \Delta p_1 + \Delta p_2 + \Delta p_3. \qquad (15)$$

Values for R and S for various seeds are given by Hunter (1983).

An allowance for packing of the seed as distinct from loose fill should be made and may be taken as increasing R and S by 20%.

Fan Selection

Means to assist in the decision as to what airflow rate should be used have been given. Once the airflow rate has been selected, conditions have been presented which allow duct sizes to be determined. From the airflow rate and duct geometry, the pressure difference across the seedbulk can be determined as discussed above, allowance being made for supply duct losses if appropriate.

Having determined the fan duty (volume flow and total pressure) it is suggested that a direct drive fan be chosen to reduce downtime and maintenance.

When selecting a fan, the temperature rise as the air passes through the fan will be relevant if a blowing system is used. The fan temperature rise Δt is given by

$$\Delta t = \frac{\Delta p}{\eta \rho_a C_p \zeta} \qquad (16)$$

where η is the total efficiency of the fan, and C_p is the specific heat of air at constant pressure. Differences in kinetic energy of inlet and outlet flow are neglected.

The effect of the temperature rise through the fan must be considered with reference to a psychrometric chart overlaid with equilibrium isosteres for the seed type under consideration.

Conclusions

The significant features of an aeration system are the airflow rate, the fan control system, and the air distribution system. The formulae and graphical information presented here should assist the reader in designing a practical aeration system for most types of storage and for most climatic situations. The reader will require moisture equilibrium data and Ergun coefficients for the seed type concerned.

Acknowledgments

The author is indebted to the Australian Wheat Industry Research Council which has supported this work and to the Australian Centre for International Agricultural Research which sponsored its presentation at this seminar.

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Notation

Abbreviations

dbt	dry bulb temperature
wbt	wet bulb temperature

Symbols

a	average weekly minimum wet bulb temperature, °C
b	average weekly maximum wet bulb temperature, °C
f	D'arcy Weisbach friction factor
l	length of duct, m
p	static pressure, Pa
Δp	difference in pressure of air, Pa
q	specific airflow, m^3/s kg or l/st
r	radius of half round duct, m
s	standard deviation of ambient wet bulb temperature, °C
t	wet bulb temperature of seedbulk, °C
Δt	fan air wet bulb temperature rise, °C
t_a	dry bulb temperature of ambient air, °C
t_o	initial wbt of seedbulk, °C
t_{ad}	dbt of ambient air, °C
v	face velocity of air, m/s
w	moisture content of air
x	distance coordinate, m
A	cross-sectional area of duct, m^2
C_p	secific heat of air, J/kg K
D	diameter of circular cylindrical store, m
F	aeration time fraction
H	height of seedbulk, m
ΔH	equivalent additional height of seedbulk caused by duct constriction, m
P_p	perforated perimeter of duct cross-section, m
P_w	wetted perimeter of duct cross-section, m
Q	airflow, m^3/s
R	first Ergun coefficient, Pa s/m
S	second Ergun coefficient, Pa s^2/m
W	width of seedbulk cross-section served by the duct, m
X	plan area of store, m^2
ε	equivalent sand roughness height, m
ζ	differential number, $\zeta = \frac{\partial t_{ad}}{\partial t_a} \mid w$ (psychrometric chart)
η	fan efficiency
θ	time, s
ρ	density of air, kg/m^3
ρ_s	density of seedbulk, kg/m^3
σ	fractional variation of static pressure along a duct
τ	storage period under consideration, s
Ω	normalised temperature time integral
Γ	ratio of velocity of temperature front (cooling) or a moisture front (drying) to the face velocity of the air.
Ξ_i	normalised seedbulk temperature

The mean of any quantity is indicated by an over-bar.

A Procedure to Estimate the Supplemental Heating Needs for In-store Drying of Paddy

R. G. Bowrey* and R. H. Driscoll†

Abstract

The air used to dry grain in ventilated stores provides both the energy needed to evaporate the moisture from the grain and the medium to transport this moisture out of the store. If supplemental heating is used to increase the inlet air temperature, the rate of moisture removal is increased and the airflow rate can be decreased, leading to several solutions for a particular set of circumstances. Depending on the relative costs of heating energy and electrical energy, one of these solutions is to be preferred.

This paper discusses a procedure to determine how much supplemental heating should be provided for in-store drying of paddy rice. A graph is provided to estimate the airflow rate required to dry paddy in terms of the inlet air temperature, the ambient humidity, and the initial grain moisture content. A second graph can be used to estimate the fan power required for various airflow rates. Using these graphs the total energy cost can be estimated for various amounts of heating, thereby allowing the most suitable level to be selected.

AT harvest, grain is hot and moist and must be cooled, dried, or protected in other ways to prevent fungal/mould growth (Mendoza et al. 1985). In dry climates this can be achieved by aeration (Navarro and Calderon 1982) and, although this technique has applications in the tropics, the ambient relative humidity is often so high that supplemental heating is required. Increasing the temperature of the air increases both the ability of the air to carry moisture out of the store and the availability of energy to evaporate this moisture from the grain.

It has been observed by many researchers (e.g. Sutherland et al. 1971; Smith and Bailey 1983) that wet paddy under aeration cools to a temperature close to the wet bulb temperature of the inlet air (i.e. the pseudo wet bulb temperature). This occurs well before the grain dries. As the grain dries the amount of heat needed to evaporate moisture is reduced, less cooling occurs, and eventually the grain comes to equilibrium with the dry bulb temperature of the inlet air. This puts a practical limit on the maximum inlet temperature allowed for long periods of time, because holding dry grain at high temperature can affect the quality.

Both the airflow rate and the inlet temperature affect the time to dry the grain at the top of the store and if the flow rate is too low this grain will be damaged by microbial activity. The need to balance heat input and airflow rate created the need for a design procedure.

Many 'ad hoc' designs have been proposed for drying paddy at the village level. However, for larger storages in countries such as Malaysia, the Philippines, and Thailand, a more rigorous approach is needed to determine design parameters for any supplemental heating system.

Description of Drying

Various models have been developed to predict the time/position profiles for both temperature and moisture content of grain during ventilation (Sutherland et al. 1971; Dung 1980). These models predict that, during ventilation with constant inlet air conditions, the temperature of the grain changes more rapidly than the moisture content and this sets up temperature and moisture zones which move through the grain at different speeds. A temperature (moisture) zone is a region of grain

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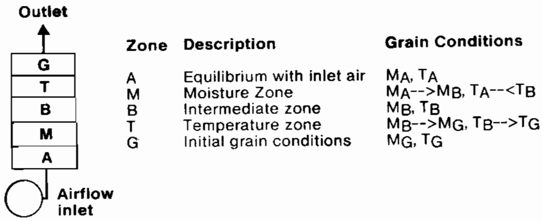

Fig. 1. Definition of zones within a bulk of drying grain.

in which the temperature (moisture) is changing. In front of the temperature zone the grain is unchanged from its initial conditions. Behind the moisture zone the grain is in equilibrium with the inlet air and in between the temperature and moisture zones there is grain which has had its temperature changed with little change in moisture content. The details of these five zones are shown in Figure 1. The nomenclature adopted in this paper is as follows:

H	humidity	kg/kg
L	grain depth	m
M	mass of wet grain	t
m	moisture content, dry basis	%
	fan efficiency	%
P	fan power per tonne of grain	kW/t
Q_f	heat input from fan per tonne of grain	kW/t
Q_h	heat input from heater per tonne of grain	kW/t
T	temperature	°C
v	superficial air velocity	m/minute
v_f	drying zone velocity	m/minute

A typical set of conditions for a ventilated paddy store in Australia is plotted on a psychrometric chart in Figure 2. The initial grain conditions are 17% moisture content (wet basis) grain at 10°C (G), dried with air at 30% relative humidity (RH) and 35°C (A). Under these conditions the grain is heated to approximately 22°C by the passage of the temperature front (B). If the initial grain temperature was 30°C the passage of the temperature front would cool the grain to 22°C. After the temperature zone has left the store the air leaves in equilibrium with grain at the pseudo wet bulb temperature and the initial moisture content (zone B). Equilibrium data are shown in Figure 3.

In both Australia and North America, grain is harvested just before the onset of winter when cold humid air is prevalent. With these low pseudo wet bulb temperatures, the wet grain near to the outlet

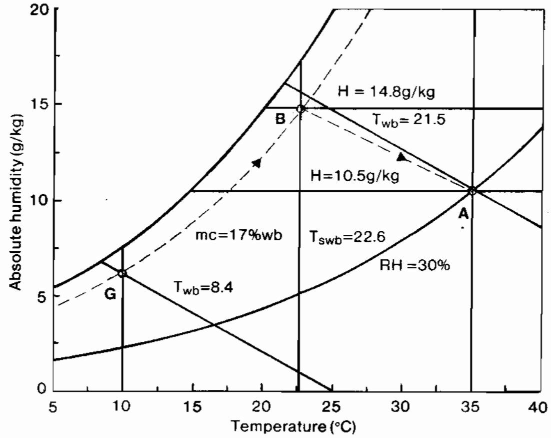

Fig. 2. Psychrometric representation of deep-bed drying of grain.

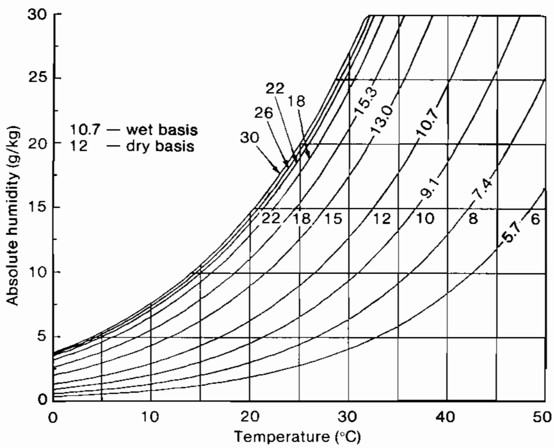

Fig. 3. Lines of constant moisture content for rice.

(zone B) can be kept for long periods without mould damage occurring. For this reason aeration at low airflow rates is acceptable and a holding strategy, whereby the grain is cooled with night air to about 5°C, is often employed. At this temperature, mould, bacterial and insect activity can be safely ignored for several months until the weather becomes sufficiently warm and dry for slow ambient drying. This is not true in the humid tropics and higher flow rates and supplemental heating are necessary (Teter 1982; R. H. Driscoll and T. Adamszak, pers. comm., 1984[1]).

[1] Pilot plant proposal for Malaysia. Analysis of rice drying in Bangkok.

Working Equations[2]

For design purposes the speed of the drying zone can be estimated from the equilibrium theory which predicts that the moisture zone is a square wave, with the air leaving the store, after the passage of the temperature zone, in equilibrium with the inlet grain at the pseudo wet bulb temperature. Based on these predictions, the speed of the moisture front can be estimated from:

$$v_f = 0.185 * v * (H_B - H_A)/(M_G - M_A) \quad (1)$$

This equation is plotted in Figure 4.

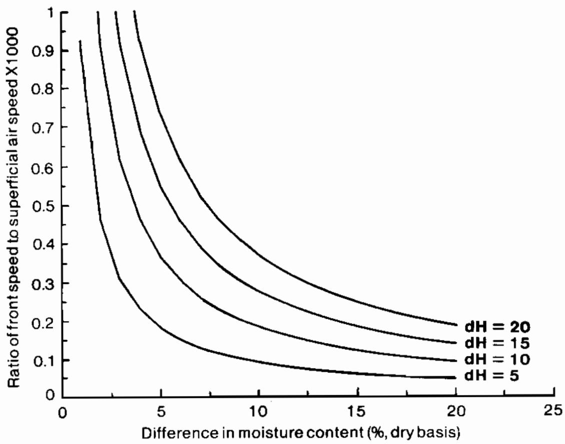

Fig. 4. Graphical estimation of moisture front speeds in grain.

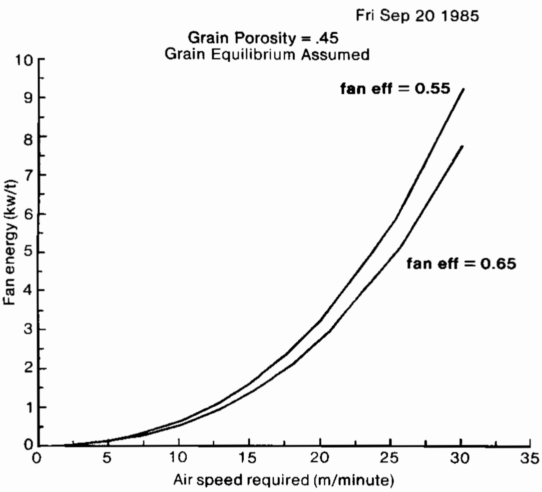

Fig. 5. Relationship between air speed and fan power required in an aerated grain bulk.

[2] All equations in this paper are based on the following data: grain density 650 kg/m³, air density 1.2 kg/m³, porosity 0.45, air heat capacity 1.0 kJ/kg K.

The fan power per tonne of grain to force the air to flow through the store can be estimated from:

$$P = (0.96 * 10^{-3}v^2 + 4.89 * 10^{-5}v^3)/kW/t \quad (2)$$

This equation is plotted in Figure 5. Because of fan inefficiencies, part of this energy heats the air and this should be allowed for when sizing the supplemental heater.

Design Procedure

To estimate the design conditions to dry M tonnes of paddy with an initial moisture content M_G in an in-store dryer using supplemental heating, the following procedure is recommended. The ambient humidity is H_A and the ambient temperature T_o.

Select design parameters:

i. time allowed for the moisture front to pass through the store (t);
ii. grain depth (L) ⟶ v_f

Estimate design conditions:

iii. select temperature out of heater T_A;
iv. calculate the airflow rate using Figures 3 and 4;
v. calculate the fan power required using Figure 5;
vi. select heater to produce temperature T_A at flow rate Q where Q = M * v/(0.65L) m³/min;
vii. estimate drying cost or other objective function;
viii. repeat until objective optimised.

Example

10t of paddy at 30% moisture content (dry basis) are to be dried within 2 days using supplemental heating. The ambient conditions are 25°C, 20 g/kg humidity. The results of this calculation, using the procedure outlined, are shown in Table 1 for grain depths of 1 m and 2 m.

Priorities for Further Research

The equations presented for drying speed are based on the equilibrium model. Further research will allow this equation to be replaced by more accurate equations which allow for the fact that the drying zone is not a square wave. The equilibrium data used in Figure 3 and the pressure drop data used in drawing Figure 5 were based on rice varieties and grain porosities common in Australia. In particular applications, these values should

Table 1. Possible design conditions to dry grain at 30% moisture content (dry basis) in two days, using air at 25°C and with 20 g/kg absolute humidity. See text for explanation.

	$L = 1$ m $\longrightarrow V_f = 3.5 \times 10^{-4}$ m/min				
T_A	30	35	40	45	50
M_A	17	13.5	10.4	8.5	7.0
H_B	21	22.5	24	25.5	26.5
v	24.5	12.4	9.2	7.3	6.6
P	4.0	0.7	0.4	0.2	0.2
Q_f	1.4	0.2	0.1	0.1	0.1
Q_h	2.4	3.6	4.2	4.4	5.0
	$L = 2$ m $\longrightarrow V_f = 7.0 \times 10^{-4}$ m/min				
T_A	30	35	40	45	50
M_A	17	13.5	10.4	8.5	7.0
H_B	21	22.5	24	25.5	26.5
v	49	24.8	18.4	14.6	13.2
P	24.8	4.1	1.9	1.1	0.9
Q_f	8.7	1.4	0.7	0.4	0.3
Q_h	—	6.3	7.9	8.7	9.9

be replaced by data more relevant to the application. Various sources of heating are available in grain drying areas, including combustion of hulls and other agricultural materials, solar absorbers, biogas, waste heat from exhaust gases, etc. The results in this paper show that temperature rises of about 10 to 20°C are very effective in reducing the fan sizes required. Consequently, relatively simple heaters can be very effective.

Conclusions

A procedure is described to estimate the reduction in fan power permissible if supplemental heating is used to increase the temperature of the drying air. Depending on local conditions an optimum set of conditions can be selected to minimise the total drying cost while drying the grain within a nominated period of time. The procedure can be used to study the cost of changing grain depth or drying time.

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Control Systems for the Aeration and Drying of Grain

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Abstract

Grain aeration and drying require a large capital investment. The effectiveness of the facilities involved can be maximised, quality can be improved, energy usage can be minimised, and labour inputs can be optimised by the application of commercially available, reliable, and economically viable controllers. Running costs can be reduced by up to 40% for a capital investment of $0.50/t.

Good intentions of management can be dwarfed by the pressure of harvest. The application of control systems to aeration and drying allows the best management option to be applied to all facilities.

This paper analyses a proposed aeration and drying system for application of possible control devices. Commercial results of the application of control systems are presented, along with the results of a simulation model of the system proposed.

Control systems allow rapid decisions to be made using past, present, and predicted conditions to achieve the objective of lowest cost, highest quality, or minimum drying time.

CONTROL systems are the means whereby a complete system can be regulated to achieve a desired result. The control can be:

1. by instruction to operators of equipment or facilities of the optimum sequence or conditions for operation — a manual system;
2. by application of simple feedback control devices dedicated to discrete operations within the system, but still regularly supervised and adjusted by a supervisor — a supervised system;
3. by application of a Programmable Logic Controller (PLC) or a computer control device capable of monitoring all conditions within the complete system, allowing rapid interaction and adjustment by the control device of all the discrete operations within the system to achieve the best management option continuously — a semi-supervised system.

Any control system requires input information. This information can range from basic details of tonnage, moisture content, and variety, through to historical information on the conditions of treatment of the grain to date and to required throughput to achieve mill requirements or to clear a wet grain backlog.

Manual System

The most widely used form of control system is the manual control system. For a manual control system the amount of information that can be collected and analysed to make a control decision is limited by time and available manpower.

A manual control system is typified by checksheets and dials for inputs, and slides and on/off switches for outputs. Decisions are made by a person who then physically communicates the output state to the devices concerned.

Supervised System

For a supervised system the opportunity for feedback control of some discrete operations will allow the supervisor time to review a wider range of information in order to make a controlling action. A supervised system is typified by checksheets, dials, electric or mechanical reaction inputs with adjustable setpoints, slides, and on/off switches or relays for ouputs. The 'decide' process can be performed manually but will normally include a number of inputs reacting directly with a dedicated output device to control a discrete

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operation in the system. The supervisor interacts with the inputs and adjusts the field of performance of an operation of the system via setpoints or by physically communicating the required output state to the output device.

Semi-supervised System

Semi-supervised control is the realisation of a dream of industrialists. By automatically controlling a process, the role of sometimes fickle and usually expensive human resources can be oriented more towards maintenance and supervision.

For a semi-supervised system the larger amount of information it is possible to analyse in a short space of time allows the supervisor to be removed from the most routine control actions and simply respond to alarm prompts, fine tune the system, or duplicate the performance identically at other locations. He can also re-allocate priorities for the system based on the demands outside the system for rapid drying of the raw material or higher output requirements for shipping or further processing, or smoothing energy requirements from a supply authority.

The semi-supervised control system is typified by selected sensors with similar electronic outputs which can be directly wired to the PLC or computer control device. A fraction of the available input readings can be presented as a printout, graphical display or tabulated display on a Visual Display Unit (VDU), or communicated to a remote facility via a modem for inspection by a supervisor. Such a report can be expanded to include a system current status report, fault report, or audit or log of system operation for energy or raw material accounting.

Aeration

The reason for aerating grain is to achieve the final objective of the improvement of storage conditions. This may be attained by moving air of the desired properties through the grain bulk until a new microclimate is produced, which will keep the stored grain from deteriorating. In all events, aeration is aimed at improving storage conditions but not grain quality. However, it often happens that aeration prevents a decline in quality.

Since aeration may have different effects on stored grain (see Fig. 1) storage conditions may be improved in different ways. These will depend on the properties of the air and on the existing

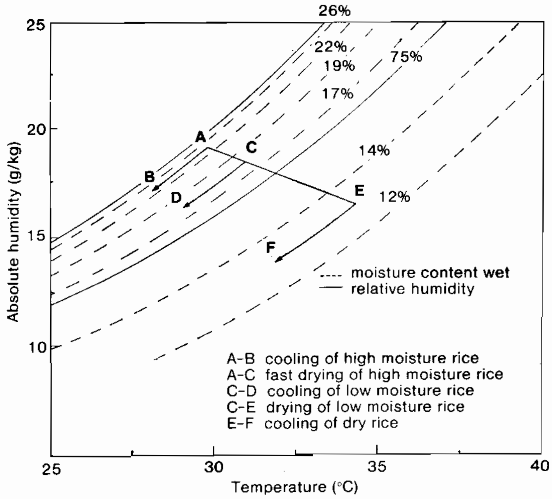


Fig. 1. Psychrometric chart of grain aeration and drying processes.

condition of the grain. Therefore, before operating the aeration system it is essential to foresee the effect aeration will have on the grain, based on the available data on the condition of the grain and the external air. Aeration control systems formalise the procedure for operation, assist in the gathering of reliable data, and can allow the application of the best management option for the economical running of an aeration system.

The objectives for operation of an aeration system are derived from the anticipated effects on the grain of the movement of air. These are:

- creating low temperatures in the grain bulk;
- equalising temperatures throughout the grain bulk;
- prevention of heating in damp grain;
- limited drying.

There are also some additional uses of the aeration system, such as introduction and recirculation of fumigants, and removal of odours and fumigant residues, though these are less frequently applied in practice.

Cooling

Cooling of grain is the most frequently sought and advantageous objective of grain aeration. If cold air is available (during winter or on cold nights), by introducing and moving this air throughout the grain mass, its temperature will eventually be lowered (see Fig. 1.). Thus, a new environment, for all living components of the grain bulk ecosystem will be created.

Aeration is very often applied in the storage of just-harvested damp grain, before being dried, especially where local drying capacity is insufficient. Aeration for this purpose is used mainly in temperate climates. and is intended to enable the storage of grain with excessive moisture content for short periods of time. This aeration is called in Europe 'maintenance of condition' ('ventilation de maintien') since it is aimed at maintaining the grain quality and preventing spoilage.

Maintenance

True maintenance of condition is applicable to the action of maintaining dry grain in a fit and saleable and consumable condition for as long as required as cost effectively as possible. An aeration control system having the ability to monitor the undesirable changes occurring in or the potential for these changes to occur in the grain bulk and summoning a remedial action is the ultimate system.

In damp grain bulks, respiration is very intensive, due to grain and microfloral metabolism. This respiration results in some loss of dry weight and produces the phenomenon called 'spontaneous heating'. Thus, heat accumulates in the grain bulk and apart from being detrimental to grain quality, the high temperatures (up to about 60°C) create temperature gradients between the heated grain and cool surrounding air. Moisture migration, brought about by the above phenomenon will seriously degrade the storage conditions and threaten the grain quality.

Aeration of paddy rice in temperate parts of Australia is carried out intermittently during the poor, ambient conditions of winter until drying can be completed in the spring. This is termed 'maintenance aeration'.

In order to prevent the deterioration processes described earlier, the aeration system, delivering high airflow rates, is put into operation almost continuously. The flow of this air through the grain bulk prevents the formation of heating foci and also eliminates the differences in grain temperatures throughout the bulk. Thus, it maintains the stored grain in a condition in which immediate damage is prevented, but it does not improve its storageability. When cool ambient is used for this aeration, some decrease of grain moisture content is obtained.

Storage of damp grain in warm climates is a problem since, at high temperatures, respiration, mould growth, and grain deterioration are accelerated. Aeration for 'maintenance of condition' would be practical in these regions during cool nights, or in the cool season only, and the aerated grain should not be too damp.

Since storage of damp grain in warm climates is very hazardous, aeration should be carried out with great care, at the highest possible airflow rates, in as shallow as possible a grain bulk, and utilising air temperatures lower than that of the grain.

It can be readily demonstrated that application of a control system will prevent overdrying. The practical reality is that application of a manual control system to overcome overdrying can be difficult, as suitable ambient conditions may only be available for short periods and at different times of the day if at all.

A significant drying effect may occur during aeration for grain cooling in large bulks. This loss of water from the grain bulk is also a loss in weight which, apart form the economic loss of saleable mass, can also indicate unnecessary running costs. A further result of overdrying can be a significant reduction in the efficiency of further processing of the grain, an example being the reduction of whole grain yield in the case of rice. In temperate climates, the loss of weight can be a significant amount before consideration of any other factors.

Equalising temperatures is a very important objective of grain aeration, especially in subtropical climates in which diurnal or seasonal fluctions in temperature occur. In this case, the purpose of aeration is not grain cooling (although the use of cool air is preferred), but the prevention of the phenomenon called 'moisture migration'.

Grain loaded into storage after harvest keeps its initial high temperature for a long time, because of its self-insulating properties. With the change of the ambient temperature during the cool season, however, the surface (and external) layers of the grain bulk become considerably cooler than the internal bulk grain. Thus, temperature gradients in the grain bulk are created, which bring about convection currents moving through the intergranular air. These currents convey the warmer air (which contains more moisture than cool air) towards the colder parts of the grain bulk. Thus, the warm air 'migrates' to the cooler surface layers. There, the cooled air deposits its excess moisture and slowly increases the grain moisture content in these parts of the grain bulk.

The moisture migration may be a slow, continuous process and, consequently, moisture will slowly accumulate in the coldest grain layers. In extreme cases, condensation of water on the grain may occur, causing rapid mould (and sometimes bacterial) spoilage. One of the typical symptoms of this phenomenon is 'crusting' of the grain surface which should be taken as a final warning that steps must be taken to prevent further damage. The most disturbing aspect of moisture migration is not the amount of damaged grain, which is usually small in proportion to the grain bulk, but the often unavoidable mixture of damaged grain with undamaged grain during unloading. This reduces the quality of the whole bulk. In addition to discoloration, mustiness, and decrease in germination, production of mycotoxins in microflora-damaged grain should also be considered. The most significant microfloral damage which has recently received worldwide attention of nutritionists is the production of mycotoxins.

Moisture migration is very marked in warm, subtropical climates in which the ambient temperature may drop considerably by night or during winter. Logically, the prevention of its occurrence will be possible by the elimination of temperature gradients throughout the grain bulk. This may be achieved by aeration with ambient air, preferably during cool nights. For this purpose, temperature should be measured throughout the aerated bulk in order to check its uniformity.

Drying

Proper control of grain drying operations is essential if the grain is to be marketable. Automatic control is preferred since spoiled grain due to underdrying and decreased value from overdrying very often results from manual control.

Much research has been done using various sources of energy for low temperature, grain drying systems, but only a few investigators have analysed control procedures for minimising energy consumption and even fewer have been concerned with grain deterioration and overdrying which can result from these strategies.

A dynamic programming method was used by Gunasakaran and Shove (1983) as an optimisation technique. Optimum flow rate of drying air was obtained for each day and average flow rate was compared at the same time with conventional flow rate. Savings were up to 15%. By limiting the length of drying time it was possible to eliminate the risk of grain spoilage. However, the efficient application of this technique requires a special control system and variable speed for the motor, and in many cases this may not be economical.

A critical path method was used by Colliver et al. (1979). A comparison of this technique with three other techniques — time clock control, relative humidity control, and continuous operation — was presented. The comparison was performed on five drying facilities; natural air drying, solar-assisted drying, electric heating assisted drying, off-peak power assisted drying, and stirring. Savings obtained by this method are not much higher than savings obtained by using relative humidity control or time clock control.

A microprocessor based control system was presented by Simmonton et al. (1981) for combination (high-low temperature) drying. In combination drying the grain is initially dried in a high temperature dryer to bring the moisture down to a level that the low temperature drying system can handle safely.

A 72 hour time limit is set for completion of second stage drying. Capacity of the first stage dryer is adjusted to obtain the required moisture content for the second stage of drying.

The authors suggest that a better approach might be obtained by changing 72 hour limit for second stage drying to a period variable according to weather conditions. It was also suggested that the higher the changeover moisture content the better the drying operation is.

Control Limits or Parameters

Parameters of ambient air available for cooling of grain have been presented in Figure 2.

Figures 2a and 2b present air available for cooling when no mechanical equipment is used. The amount of this air is limited and in some circumstances there may be not enough of it to cool the grain to the required temperatures.

Figures 2c and 2d show that the required parameters of cooling air can be obtained regardless of ambient air parameters by employing equipment for mechanical cooling of the air stream.

For proper control of cooling two requirements have to be fulfilled:

- the air supplied must be of the required parameters. This can be achieved by employing wet bulb, dry bulb, and humidity sensors;

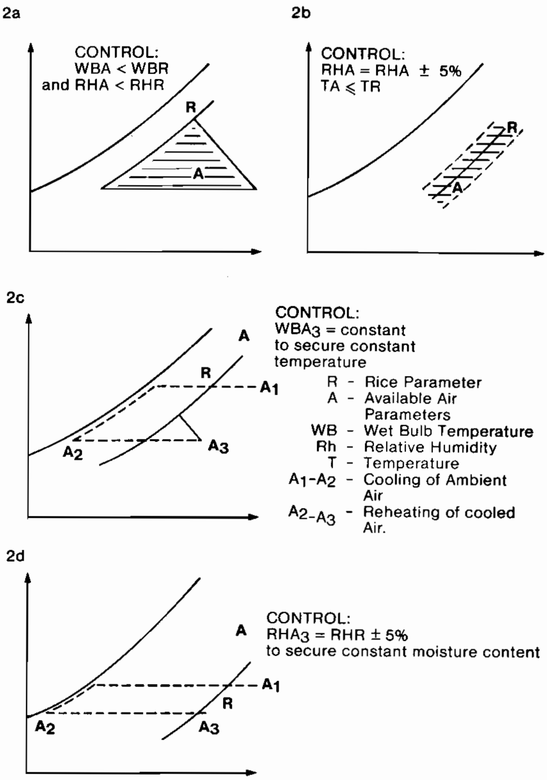


Fig. 2. Availability of air for cooling grain represented on psychrometric charts.
(a) Cooling of high moisture grain with ambient air.
(b) Cooling of dry grain with ambient air.
(c) Mechanical cooling of high moisture grain.
(d) Mechanical cooling of dry grain.

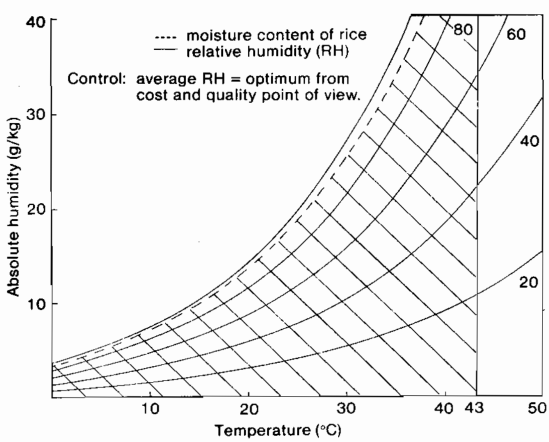


Fig. 3. Availability of air for drying grain represented on a psychrometric chart.

- the length of the cooling process must be controlled by means of a timer based on statistical or feedback information.

Parameters of air available for drying have been presented in Figure 3. Decision about which parameters should be chosen is dependent on availability of supplementary heating as well as on data obtained from control simulation. The results of this simulation take into account the costs of energy and quality losses.

Simulation results for in-store drying with supplementary heating for a relative humidity setpoint ranging from 45 to 75%, bin depths 3 and 6 m, velocity of supply air ranging from 1.5 m/minute to 4.5 m/minute for two locations, Alor Star and Leeton, are presented in the Appendix, Figures A1-A4. It can be seen that the optimum setpoint for most of the systems tends to be around 55% and 60% for Leeton and Alor Star, respectively. For deeper beds, the optimum tends to be in the lower range of humidity and vice versa for shallower beds.

The principle of self-tuning, constant relative humidity control is presented in the Appendix, Figures A5-A6. The main advantage of this control is that it does not require statistical analysis of the local weather data. The controller compensates for any changes in the velocity of the supply air and ambient conditions. Because the process of in-store drying takes a long time (from 100 to 2000 hours) short periods of low and high humidity can be ignored. The effects of these periods are minimised by diffusion and absorbtion phenomena, so the consequences are minimal. Long term average relative humidity is the only factor which has to be kept at an optimum level.

Costs

Energy

Figure 4 illustrates the increase in the cost of basic energy sources used in the aeration and drying of paddy rice in Australia. These cost increases have not been matched by increases in the price obtained for rice. In an effort to maintain returns to growers, or processor profitability, closer control of these increasingly expensive resources must be achieved. This dictates some form of control system. If the rapid rate of price increase continues then equally rapid reaction by management to control these costs is justifiable.

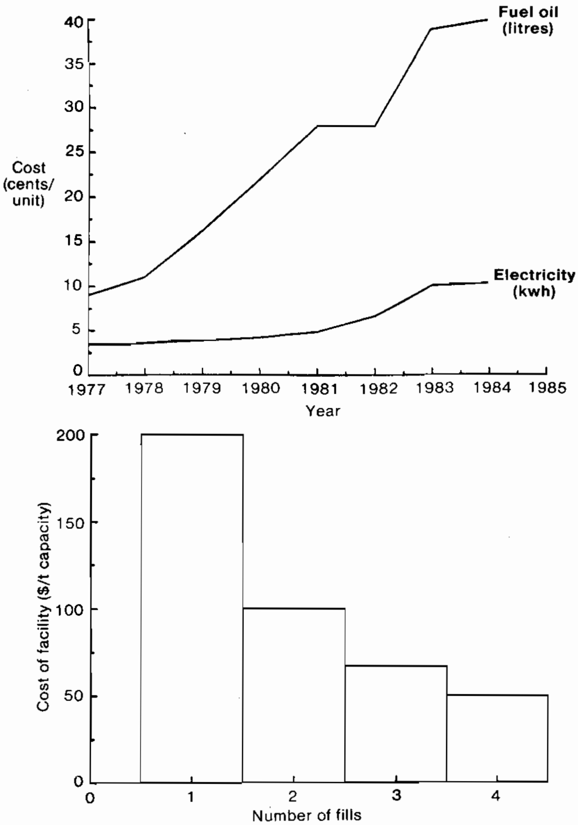


Fig. 4. (a) Increases in costs of electricity and fuel oil in Australia, 1977-1984.
(b) Capital cost per tonne versus utilisation of grain drying facilities.

Quality

Costs involved in drying processes can be minimised by proper design of control systems. Examples of some of the costs which are commonly ignored are presented in Figure 5.

As can be seen losses from overdrying, underdrying (dry matter loss), or breakage can be quite high, sometimes even exceeding energy costs, and it is therefore necessary to take them into account when analysing the economics of the drying processes (see Appendix A for details).

Labour

The extent of any reduction in labour costs that may occur following implementation of a new system is hard to predict. Labour is certainly used more effectively within a well-defined system. Workers are released from more menial tasks and can apply themselves to managing the system rather than reacting to individual events.

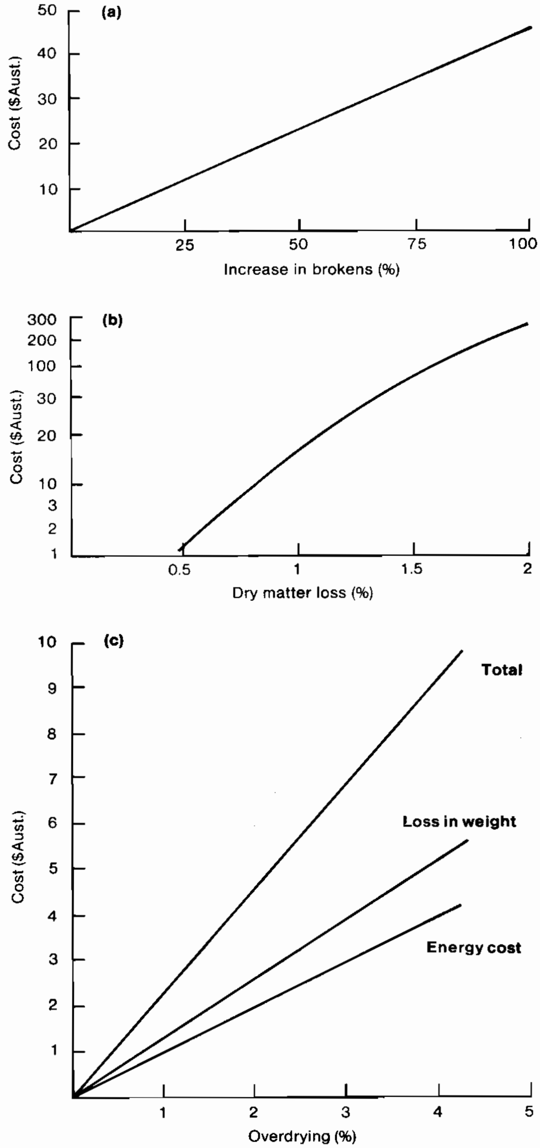


Fig. 5. Costs associated with drying of rice.
(a) Increase in brokens.
(b) Dry matter loss.
(c) Overdrying.

Facilities

The cost of energy to dry grain can exceed the cost of production (Gunasakaran and Shove 1983). The capital cost of constructing and equipping facilities for drying with services and controls is also high. The opportunity to re-use these capital intensive facilities has been graphically demonstrated in Figure 4b. This simple illustration shows the cost/tonne effect of fast turnover of grain through a drying facility. For tropical climates with two crops per year, the opportunity to process grain through a grain drying facility a number of times in each harvest reduces the marginal return required from each pass. The application of more sophisticated control systems to optimise the use of these facilities by tight control of the drying process can be demonstrated if extra usage of the facility is expected.

System Analysis

Elder (1983) described a control system for cooling based on a time-proportioning device operated by either thermostat or humidistat. Morey et al. (1979) also used humidistat, thermostat, and time clock controls for reducing energy consumption. Simmonton et al. (1981) reported a control system for a combination dryer incorporating a logarithmic drying model and a short-term weather forecast.

Most reports in the literature identify problems of equipment inadequacies. Apart from the CSIRO controller all others cited were of one-off experimental units. Mittal and Otten (1983) comment that no automatic system is available to control the drying process under greatly varying conditions. Ricegrowers' Co-operative Mills, Australia have experience gained from operating two computer-controlled aeration and drying depots for the safe drying and storage of paddy rice in Australia for the past five years. For the 1985 harvest a further eight sheds were installed with PLC controllers to supervise fan and supplemental heater action during drying and to allow for maintenance aeration of the paddy when dry.

In the absence of equipment failures, the next most commonly reported shortcoming of supervised and semi-supervised systems is that during on-off operation wet grain at the top of bins can be put at risk. None of the devices mentioned incorporated feedback information on the grain in the bin. They relied solely on simulated predictions.

Figure 6 demonstrates the possible decision-making paths for a manual operator of a facility, and the degree to which this decision-making can be reduced by the application of from some simple discrete process controllers up to a complete system controller. This figure also highlights the time taken by a supervisor to retrieve the data necessary to make his decision and then act with the system control outputs. The final case is the rapid critical path selection that can be performed by a semi-supervised controller which is directly connected to inputs, has decision-making ability, and can communicate directly with all necessary outputs for tight control of the system.

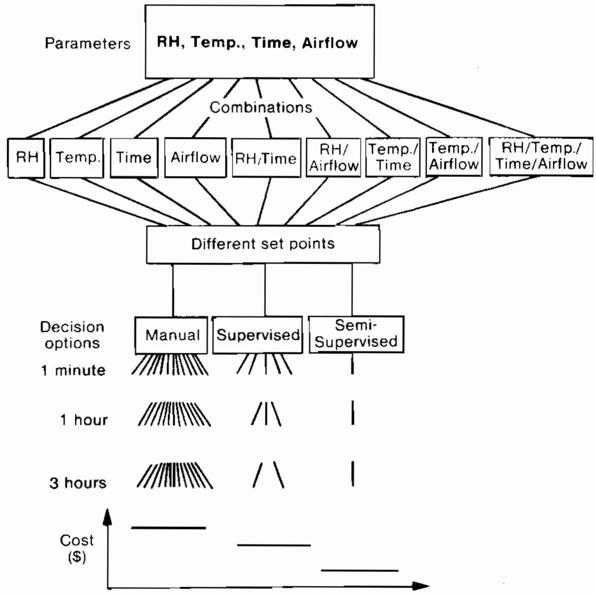


Fig. 6. Diagram of control parameters and decision options in grain aeration and drying.

Ricegrowers' Co-operative Mills Ltd, Australia operates a harvest management computer-based data information system for the manual control of the aeration and drying of 600 000 tonnes of paddy rice storage. The initial tonnage and moisture content of the paddy in the flat-bed storage bins is input to the computer. Daily moisture and temperature readings of all bins are input to the computer and together used to recommend a manual operating procedure.

The recommended manual program is manipulated by the aeration supervisor who is removed from the daily function of turning on fans and can observe and evaluate weather patterns and critically review the effect of the strategy applied to date on the objective of supply, at the lowest drying cost, dry paddy for milling.

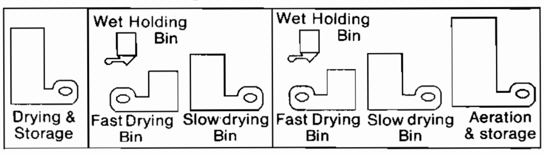
A significant problem can arise with bulk in-store drying if adequate moisture segregation is not practiced. For a drying control system to operate effectively, the initial and final moisture contents of all the grain in the bulk must be without gross deviation. In a grain bulk the presence of significantly different grain can prove disastrous, this in no way reflecting on the efficiency or otherwise of the drying control system.

System Comparisons

Simmonton et al. (1981) indicate the complexity of decision-making involving a combination drying system and suggest that an optimised algorithm incorporated in the software of a microprocessor based controller will allow application of proper management and control essential for successful grain drying operations (see Figure 6).

Systems

Figure 7 indicates the increasing complexity of the available data or inputs for use in the decision making process as the system becomes more complex. It also show the increasing number of outputs that must be manipulated to achieve the level of control desired with increasingly more complex systems. The decision making process becomes more complex when the possibility of flexible use of all the facilities is considered.



1 Stage	2 Stage	3 Stage
Inputs		
Grain Moisture/Temperature Ambient RH Ambient Temperature Time of Drying Fan actually on Bin level	3 1 1 2 3 3	4 1 1 2 4 4
Outputs		
Fan on Fan off	3 3 Transfers H-1-2 Possible 2-H-1	4 4 H-1-2-3 H-2-1-3 H-3-1-2 H-1-3-2
Decision		
Fan on/off Conditional on -RH -Temperature -Time	Fan on/off Conditional on -RH -Temperature -Time Bin. No 2 Available Harvest Rate	Fan on/off Conditional on -RH -Temperature -Time Bin. No 2 Available Harvest Rate Bin. No 3 Available Storage needs

Fig. 7. Demonstration of the increase in control functions in complex systems, such as automated grain drying and aeration.

Figure 7 presents one part of a complex situation. For a large facility with different grains being received, of different varieties and at different moisture contents and quality grades, with multiple storage bins available having multiple fans and possibly supplemental heating to supply varying milling requirements, or the maintenance of viable seed, etc., the management becomes quite complex.

Using a control system, different situations can be foreseen (modelled), the action decided upon, and that procedure used for all future occurrences.

The interaction of the individual components of the drying and aeration system can be optimised for different situations and that procedure used repeatedly.

Results of Control

COOLING

The principles of the control system designed by CSIRO for the Australian wheat industry are shown in Figure 8.

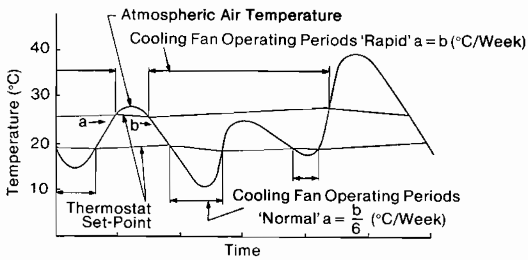


Fig. 8. Diagram of operations of CSIRO time-proportioning aeration fan controller.

Current models of the time-proportioning controller provide two settings: RAPID giving an average of 12 hours per day for initial cooling, and NORMAL giving 25 hours per week (on average). No initial setting is required because the controller action is self-calibrating always homing towards atmospheric temperature.

The major feature of time-proportioning control is that it ensures regular aeration through the seasons without supervision. Excessive aeration cannot occur, and the cost of operation is predictable.

However, there is no control of the inlet air humidity which in some circumstances can cause significant problems.

DRYING

An example is presented in Figure 9 of the result of management of an aeration and drying facility

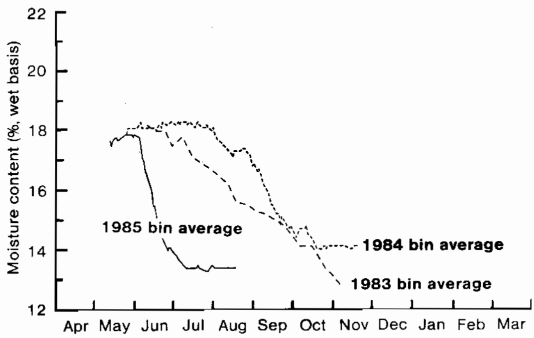


Fig. 9. Comparison of bin drying of paddy in Australia before and after introduction of overdrying management (1984) and supplemental heating under automatic control (1985).

by application of different control systems over a period of three years. This information is from Ricegrowers' Co-operative Mills Ltd, Australia. The facility illustrated is an aeration bin of 3000 t capacity. This bin has an airflow rate less than that typical of most Australian drying and aeration facilities: 2.56 m/min at a grain depth of 6 m. The plot for all years is the average moisture content obtained from regular manual reading of moisture/temperature sensors probed into the bin at the completion of grain inloading. There are 18 sensors located at top and middle levels in the bin.

The year 1983 shows typical historical lack of control with the priority on drying with scant regard for overdrying.

The 1984 plot shows that, even though better ambient conditions prevailed, little drying was achieved during winter due to cost management strategies applied. Also, overdrying was controlled due to application of a manual control strategy using daily weather recording thermohygrographs.

The 1985 plot illustrates the dramatic effect of the application of Liquid Petroleum Gas (LPG) burners to existing fans to achieve a 4.2°C temperature rise above ambient when turned on by a supervising PLC. The control strategy essentially relies on a relative humidity (RH) set point for burner operation with a high RH limit for system shutdown in the event of rain. The control system also monitors the ambient RH and temperature sensors and initiates alarms for gross failure of either sensor within any 16 hour period. The system also logs fan and burner operating hours and provides a maintenance aeration facility for programmable hours/week-month at programmable RH windows and at programmable time windows to take advanatage of off-peak electricity rates.

In order to optimise in-store drying, control systems simulation models for various control performances have been developed, for example a model with selftuning relative humidity setpoint.

The principle of this model is that the humidity of air supplied to the drying system is at constant average relative humidity in both systems with supplementary heating and systems based on ambient air aeration. This constant average relative humidity of supply air is obtained regardless of variable weather conditions or possible oversize of supplementary heating system. This is done by switching the fan or supplementary heating on or off.

In this way one avoids fluctuations in the bottom parts of the bin which if excessive cause additional quality losses due to rice breakage. At the same time, full control of the rice final moisture content is achieved and it can be set at an optimum level.

Control Systems (Canada)

There are approximately 200 large commercial grain dryers and a total of more that 600 off-farm drying operations in the province of Ontario, Canada. Altogether these facilities use about 122,000 cubic metres of natural gas and propane each year to dry approximately 160 million bushels of corn. The annual cost in fuel alone is close to $22 million.

Grain drying accounts for 24% of the cost of production of grain corn, but with the new automatic systems monitoring and controlling the grain drying process, the annual costs can be cut by 10%. In addition, reduced spoilage and shrinkage, higher quality of grain resulting from the automatic controls of the process will increase the product revenue and dramatically improve the operating position of the installation.

Operating data gathered over the last year show that the advantages of the system include: reduced operator time, faster and more precise drying, reduction in unnecessary moisture pockets, and safer storage.

Future Research Activities

Further research and development work is needed before control systems can be applied to aeration and drying facilities in the humid tropics.

The following is a brief catalogue of the information that this work must provide.

1. Determination of the safe drying conditions in the tropics: air and grain limits for RH, temperature, and time; evaluation of final moisture distribution.
2. Determination of the safe storage conditions: air limit for RH; grain limits for temperature and time.
3. Comparative evaluation of commercially available RH sensors (self-cleaning chilled mirrors, capacitive, resistive, tension) in dusty, humid environments.
4. Comparative evaluation of suitable commercially available control devices under hot, humid tropical conditions.
5. Determination of costs involved in drying of rice to lower moisture contents (the lower final moisture contents are sometimes advisable for tropical countries where long storage periods are used and no refrigeration is applied to prevent quality losses).

Conclusions

Aeration is used to produce cooling in grains where, in the case of wet grain, self heating is possible due to the respiration of the grain and the microflora associated with it. In the case of dry grain, it is used to reduce insect activity, preserve the nutritional and aesthetic qualities of the grain, and to assist fumigant action and/or prevent overdrying.

The air parameters for drying should be optimal. The optimum is a function of drying equipment, energy costs, quality loss costs, and milling requirements. The best way to achieve it is by a semi-supervised control system, but in smaller installations this could prove too costly. However, as the cost of programmable control devices continues to drop and their power increases it becomes more realistic to plan for their inclusion in the future by the selection and application of sensing and control devices which can be readily integrated into an automated system.

The most readily applicable control system for aerated and in-store dried grain in the humid tropics would currently be a manual control system.

Developing from a manual control system to semi-supervised control has merit in allowing the operator to identify the key inputs required, the best decisions for differing situations, and the form in which the outputs should be controlled.

This then forms the strategy for the semi-supervised control system. An existing manual control system can be converted to higher levels of automation.

In guiding the operator to the key input parameters and logically developing the resultant controlling action, significant progress can be made in overcoming problems in the pressure of harvest and the stressful task of management.

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Appendix

Simulation results for in-store drying with supplementary heating, at Alor Star, Malaysia and Leeton, Australia.

The following assumptions have been made for the analysis.

1. The electricity price is 0.8¢ kWh.
2. The LPG price is 40¢ kg.
3. Dry matter loss cost has been calculated according to the formula (after Pierce and Thomson 1979):

   cost = ((dml/0.5)**4)* 0.01 *140.0

   where

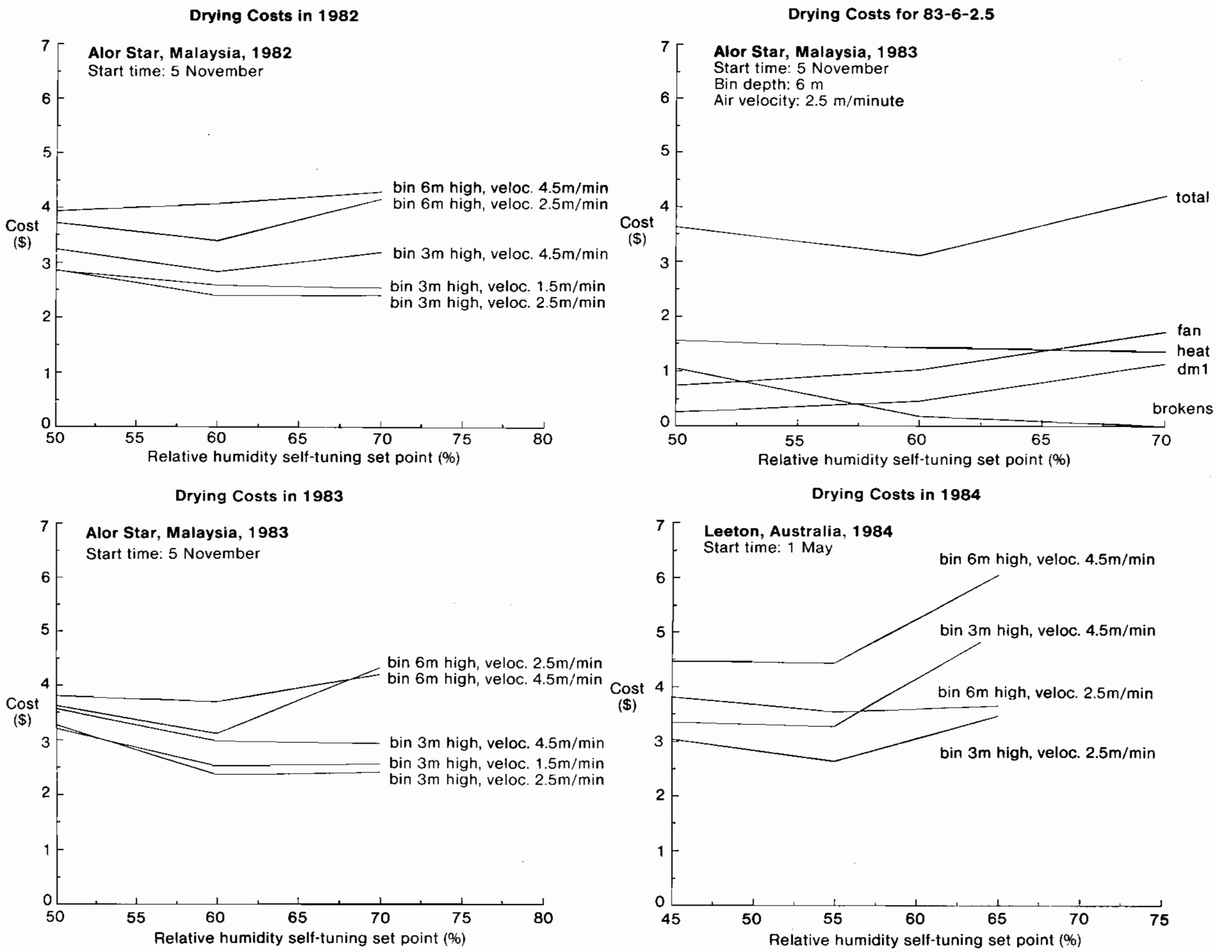
   dml is the percentage of dry matter loss.
4. Brokens level has been estimated according to the formula:

   percentage of

   brokens = 0.06548*wb**2-3.837*wb + 38.82

   where

   wb is moisture content of rice, wet basis.
5. Initial rice moisture content was at 19.3% wet basis and final was 14% wet basis and the drying period was starting on 1 May 1983 and 1 May 1984 in Leeton.
6. Initial rice moisture content for Alor Star was 18% and final was 14% and drying period was starting on 5 November 1983 and 5 November 1982.
7. Paddy price is $140/t.
8. Initial percentage of brokens is 10%.



Figs. A1-A4. Drying costs for grain based on simulated control for different relative humidities, bed depths, and airflow velocities.

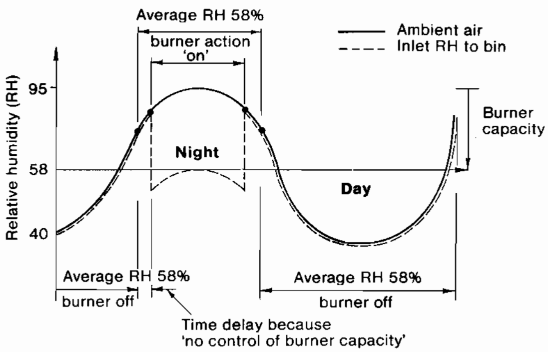


Fig. A5. Principle of self-tuning, constant relative humidity (RH) control, involving supplemental heating with constant heater capacity.

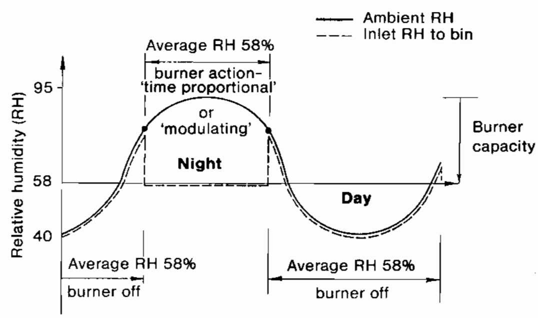


Fig. A6. Principle of self-tuning, constant relative humidity (RH) control, involving supplemental heating with variable heater capacity.

Design of Aeration and In-store Drying Systems Session Chairman's Summary

G. R. Thorpe*

THE first presentation in this interesting session was Mr Teter's paper on design parameters for storage and handling system structures. It summarised the fundamental biological and physical information that must be known before a grain handling system can be specified and designed. Many of the data are already available, e.g. we now have very sound data on the air/water vapour system. Because of variability in grain properties, equilibrium moisture data tend to be a function of variety and history. In this sense, hygroscopic data can be used as a guide. They are hard, fast, and immutable.

Likewise, parameters defining ΔP versus Q are, in economic jargon, 'rubbery'.

Mr Teter also gave data on dry matter loss for paddy, and there are, understandably, some discrepancies between two studies he referred to. I believe we must have further quantitative studies on this phenomenon because of its importance on the storage ecosystem.

Because insect population growth is much slower than the build up of heat, parameters for insect population dynamics are probably known sufficiently well.

Mr Teter places a good deal of faith in the deterioration index. I have reservations, because the index considers only the air state. The state of the grain must also be considered.

Dr Hunter's paper had four main themes:

- selection of airflow rates and aeration strategies;
- static pressure regain in aeration ducts;
- pressure drop calculations across grain bulks;
- fan selection.

The paper showed how, for a given climate, the airflow rate and aeration fraction can be chosen to minimise the temperature–time integral of the grain bulk. This assists determination of the technical optimum. The static pressure regain charts, and formulae for pressure in bulks produced by Dr Hunter, although very sophisticated are easy to use. Pressure drop formulae are also very easy to use and perhaps should be distributed in the form of computer software.

The paper by Dr Bowrey and Dr Driscoll entitled 'A procedure to estimate the supplemental heating needs for in-store paddy drying' was a paradigm of simplicity, elegance, and usefulness. It described a procedure for dryer design that uses a psychrometric chart and a simple calculator. It is not only of great practical use to the engineer, but also has considerable teaching value.

Mr Sutherland pointed out that the Bowrey-Driscoll approach is most accurate when the drying front remains within the bed. I note here that Mr Sutherland's own work is also easily programmed and potentially of great value.

I would add the caveat that these simple models, although useful, cannot account for heat of respiration. They also imply a step input of airflow rate and air state.

The last paper in the session, by Mr Pym and Mr Adamczak, dealt with control systems for aeration and drying. It highlighted the value of powerful numerical models of the drying process. These models can handle variables such as:

- air state — temperature and moisture content;
- grain state — temperature and moisture content;
- airflow rates
- stochastic influences — variations in grain state with depth and climate;
- storage design, hence capital cost;
- power requirements, hence running cost.

The integrating capacity of the models permits realistic attempts at economic optimisation to be made.

Other factors can be incorporated into other models. These include the rates of decay of pesticides, insect population growth, and dry matter loss. As yet we cannot quantify all quality indices, particularly in the humid tropics. However, I am pleased to note that this issue is being addressed in various ACIAR grain storage research projects.

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Economics of Aeration and In-store Drying

Loss Assessment — Towards a Fuller Comprehension of Postharvest Loss

R. A. Boxall, D. J. B. Calverley, and P. S. Tyler*

Abstract

The major developments during the past decade in connection with postharvest loss assessment and loss reduction programs in developing countries are reviewed. The relevance of the work is appraised in relation to current postharvest problems and a proposal is made for the better use of existing and future loss assessment data in food strategy planning. The prescribed methodology has been adequate for assessment of losses at farm level, but there is a lack of proven guidelines for the commercial sector. Such guidelines are needed and should embrace a wider approach that is more concerned with improving the efficiency of the system.

THIS paper briefly reviews the state of the art of loss assessment within the postharvest system. The approach that has been followed in the past, the methodology used, and the way in which measurements of loss have been utilised, are described. In the light of experience, some general conclusions are drawn and suggestions made for future development in methodology. The problems facing grain marketing organisations, especially those in Southeast Asia, in procurement and conditioning for storage of paddy, are seen as being a major area where there is concern over losses. Proposals are made for their more objective assessment.

It is concluded that the baseline against which loss has to be evaluated should be a grain quality and pricing structure that is acceptable to the consumer. The quality control objectives of marketing organisations must reflect these customer requirements and cost-effective measures should be employed to contain food quality losses within the objective limits. The implications of introducing optimal technical procedures for loss containment are therefore considered within overall policy and planning strategies.

The Background to Loss Assessment Studies

The degree and extent of losses of grain after harvest is widely held to be a matter of concern, as also is the need to reduce loss and make improvements in the handling and storage of grain. There has been considerable activity in the field of postharvest loss assessment and loss reduction in the last 10 years. This activity was stimulated by the 1975 Resolution of the Interdepartmental Sub-Committee of the VIIth Special Session of the United Nations General Assembly, which committed member states to reduce postharvest losses by 50% by 1985. It is therefore timely to assess the achievements to date and to consider the requirements for the future.

An early review by Howe (1965) of the available information on postharvest losses, and a later one by Adams (1977), clearly showed that many of the data on the extent and types of losses were not particularly meaningful, up to those dates, and certainly did little to assist identification of targets for loss reduction programs. There was a clear need to improve and standardise the methodology for loss assessment in order to justify more firmly the development and introduction of measures designed to reduce losses in an appropriate and economical way.

Recognising this need, in mid-1978, the American Association of Cereal Chemists, with the aid of a grant from the United States Agency for International Development to the League for International Food Education, began to prepare a methodology for assessing postharvest grain losses with emphasis at the farm level. As a result of this initiative, a manual (Harris and Lindblad 1978) was published to provide the means whereby postharvest losses might be established in a

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standardised and meaningful way so that effective grain loss reduction efforts could be undertaken in developing countries. It was recognised that because of the enormous variability of local postharvest systems, no complete or definitive methodology for all situations would be practicable. Nevertheless, the manual provided acceptable guidelines to meet a variety of requirements and it is fortunate that many of the methodologies adopted within loss assessment and reduction projects have been based extensively on that suggested in Harris and Lindblad (1978). The manual detailed the techniques available for the measurement and interpretation of losses incurred during threshing, drying, storage, and milling for the major cereal grains as well as those arising from a range of specific causes including insects, moulds, and rodents. A major difficulty experienced in compiling the methodology was that the authors necessarily drew heavily on experiences gained from developed countries and limited specific examples from some developing countries. A detailed knowledge of the wide variety of systems in which assessments would be attempted was not available and consequently the difficulties encountered in applying the methodology could not be foreseen.

In reviewing the use to which the methodology has been put, it can be seen that most work has been devoted to farm and village level operations as was intended, and generally the prescribed techniques have proven suitable for studies in simple postharvest systems and, more specifically, in storage at the farm level. Experience has demonstrated the importance of a preliminary survey to provide an insight into the possibilities for loss reduction. Some major shortcomings of projects have arisen during the planning stages. For example, objectivity has not always been clear, particularly in relation to how, once obtained, the data on losses will influence decisions on the subsequent remedial actions to be employed. Sometimes loss assessment has been undertaken seemingly only to justify a course of remedial action which has already been decided upon. It may therefore be asked why the loss measurement was required. Also, an elaborate, time-consuming, and expensive program of gathering loss data has sometimes been embarked upon when a decision on the degree of loss reduction justified might have been made on the basis of a short preliminary survey.

The methodology of Harris and Lindblad advocated taking an early overview of the whole postharvest system in order to understand the food grain supply system before beginning an in-depth examination with a view to measuring loss. However, the methodology was designed to be applied to the on-farm sector and was not suited to detailed study of the whole system. The tendency has been to direct efforts towards one component, which is identified as in need of attention, without necessarily appreciating that this, in turn, may have far-reaching consequences to the system as a whole.

For example, the results of work at the farm level with maize, paddy, and other cereals have shown that the traditional system is efficient but problems arise when new, high-yielding varieties, or multiple-cropping techniques are introduced. Such innovations disturb the traditional capability to conserve grain, increase the risk of loss, and may place an additional strain on procurement and marketing facilities. The farmer has to face new and intractable problems with an increased quantity of produce. The traditional handling, drying, and storage systems are found to be inadequate, the characteristics of the crop are changed (often to a softer grain which is more susceptible to mould and insect damage), and the timing of the harvest and subsequent operations may be switched from a favourable dry season to an unfavourable wet season. All of these factors have made the on-farm postharvest system more vulnerable to loss. The recommendation must therefore be made that changes to traditional agricultural practices should never be introduced in isolation. Rather, they should be made only after due consideration of the full implications of the change.

Conclusions from Experience to Date

Experience has shown that, despite the difficulties which arise when the traditional farm system is disturbed, many of the problems at farm level could be solved by integrating appropriate postharvest loss reduction techniques into the package of improvements (seed, fertilisers, improved cultivation practices, etc.) which are offered to farmers to increase production. This might be achieved by first incorporating postharvest activities into Farming Systems Research Programs which aim to link research achievements with the needs of the farmer and community by providing a realistic assessment of what changes are feasible and acceptable under existing or changing conditions. This would ensure that efforts are aimed at containing postharvest losses within the acceptable limits of the particular traditional system. The introduction of change in agriculture requires a thorough understanding of the problems it will cause, sound technical advice to meet them, and an effective training and extension program for implementation.

There are still many aspects of farm level operations needing more study and research to establish the optimum methods of harvesting, drying, handling, and storage appropriate to the total farming system. However, trained and mobile extension staff can make a significant improvement to small-scale storage by the application of known and established techniques where appropriate. One approach which is gaining favour is the use of a national team of research, training, and extension staff who identify the problems, evaluate possible solutions, make suitable recommendations, and assist the existing government extension workers to implement the recommendations. Progress is evident, but it is necessarily slow, and many farmers are still inclined to selling their produce early in an attempt to minimise their losses, thereby placing an additional seasonal burden on central procurement and storage systems already overloaded because of their need to cope with increased total production.

Early loss-assessment studies were directed towards the farm level, and particularly towards storage. On the basis of estimates that between 60 and 70% of food grain in developing countries is held at farm level, the potential benefits of loss reduction activities seemed to be greatest in this sector. However, in view of the relatively slow progress in introducing change at the farm level and the limited postharvest research and development resources relative to the crop production sector, it is perhaps wiser to concentrate what resources are available upon the commercial sector. The benefits of loss assessment/reduction activities in this sector may, after all, be greater and achieved much more quickly, at least in the short term. There is an urgent need to pay greater attention to the commercial sector now that more countries are becoming self-sufficient in food grains, with the marketed surplus produced by small farmers becoming a predominant source of a nation's food supply. The commercial sector's response to these surpluses of grain is to store for longer periods or to begin to export, and this is particularly true of countries in Southeast Asia. However, the farm sector must not be overlooked, because inevitably changes or improvements in the commercial sector will result in a reduction of quantitative and qualitative losses elsewhere, particularly if accompanied by a price incentive. Similarly, developments at farm level, although they may be slow, will have consequences for the commercial sector.

Little systematic work has been undertaken on assessing losses in commercial operations. Some attempts have been made to apply the methodology of Harris and Lindblad in this sector. The few loss assessment studies which have been done are found to be either insufficiently comprehensive or insufficiently complete in the results obtained. Many have been primarily concerned with measuring deterioration due to physical, chemical, and biological factors in storage (La Gra et al. 1982). However, it is apparent that there are overriding factors, such as deficiencies of management, which defy easy quantification.

A particular lack is of studies where losses have been evaluated in the commercial sector along with those in the farm sector in order to obtain a complete picture. A major inhibiting factor may be the absence of a prescribed methodology immediately applicable to procurement, handling, storage, and distribution operations, but there may be other reasons such as the difficulty of coordinating studies that involve both the production and commercial sectors.

One requirement might therefore be to combine a series of measurement techniques derived from the experience gained from work in the farm sector, with a description of how better to evaluate the various commercial operations. A suggested approach to solving problems in commercial storage has been outlined by Hindmarsh and McFarlane (1983) who stress the overriding importance of adapting the technical developments and improvements to fit the existing management system. Such an approach can be aimed towards reducing losses to an agreed level.

To date there does not appear to have been a quotable example of a loss assessment study being used as the tool to both identify loss and for the subsequent evaluation of the effectiveness of a loss reduction program. Until such a complete procedure has been followed and the value of the loss monitoring effort has been demonstrated, loss assessment remains hard to justify.

Facing Up to Current Requirements

Experience with loss-assessment studies confirms that a prerequisite of national post-harvest loss reduction programs is a firm government commitment together with the necessary infrastructure and finance. Sadly this commitment has sometimes been lacking even though a short-term commitment to support a project has been made. On completion of the project, national priority has tended to shift away from the post-harvest sector and towards, say, crop production. Similar observations might be made about programs designed to increase production or to improve marketing. Only when such programs are brought under central control at the planning stage can an appropriate national food strategy be developed.

In addition to the central planning implications of introducing a policy to contain losses, there are obviously technical aspects which have to be considered within the operations of a marketing organisation. There is, therefore, an urgent need to adopt a broader approach to loss assessment and loss reduction which takes account of overall policies for both food production and food distribution. This is discussed under three headings.

Food Strategy Planning

A potentially useful tool in food strategy planning is the Food Balance Sheet Equation, either for cereals and pulses generally, or for specific commodities. The equation is designed to relate national production data to actual or projected per capita consumption. It takes account of exports, imports, the use of a commodity for animal feed or as seed, and postharvest food waste. Recent experience in relation to food strategy planning in Africa has shown that substantial amounts of data of value to the preparation of the Food Balance Sheet Equation already exist or are being collected on a regular basis, but they are rarely aggregated and are therefore not fully used. Postharvest loss data may fall into this category but there is an identified need for better, objective measurements of postharvest losses of food crops.

In the past, postharvest loss data have been used largely to create a general awareness and either to draw attention to waste and inefficiency, or to focus attention upon aspects of the postharvest system in order to justify a loss reduction program and to enable priorities to be determined. However, the same data could equally be used to improve the reliability of estimates of crop yields, totals stored or handled, and the amounts available for consumption. As far as is known, there are no examples of reliable loss survey data being incorporated in national statistics for food production or utilisation. Loss figures are used, but these are usually either informed 'guesstimates' or are obtained by difference simply to explain the imbalance between two sets of data which should be in agreement.

It would seem to be a relatively simple matter to begin to incorporate postharvest loss data into national statistics which can be used for food planning. The technical resources needed to obtain such data are often well established and a standardised methodology for assessing losses is already prescribed. However, it is questionable as to how useful these data would be if the related information were incomplete. Experience has shown that production, marketing, and consumption figures are sometimes suspect. The answer to the question is that the provision of at least some credible data must be of assistance in improving the accuracy of the Food Balance Sheet Equation, but the first priority, at least in some countries, is the need to improve the overall capability to strengthen the objectivity of and capacity for data-gathering and to improve the critical assessment of data.

Ideally, the responsibility for the gathering and processing of such data must be accepted by a central Department of Statistics and Planning, which can bridge the gap which often exists between Departments of Agriculture, Food, Commerce, etc. Hitherto, the stimuli for obtaining estimates of postharvest loss have come from staff in research organisations, field services, or even aid donors specifically concerned with the post-harvest sector.

In addition to achieving acceptance of loss data in overall planning, there is need to continue to monitor developmental and technical aspects of current postharvest practices. The significant changes that are taking place at the farm level and their effects on national marketing organisations have been noted earlier. Organisations find that storage operations which were satisfactory for several months storage are inadequate when the storage period is extended up to 12 months or longer.

If the currently accepted recommendations for good storage practice are put into effect, storage losses could be contained and even reduced. While evidence suggests that there exists considerable inertia and opposition to change which inhibits the application of different operations or procedures, this should not deter a continued and sustained effort to improve storage practices and encourage their adoption as far as possible.

Technical

Insect pest infestations can always be expected and ability to control them using safe and effective pesticides cannot be assumed. Resistance of many of the important storage insects to the insecticides currently used to protect cereals or to disinfest cereal storage is now widespread. Recently, significant resistance of storage insects to phosphine has been reported (Tyler et al. 1983) and the effectiveness of phosphine disinfestation procedures requires close examination. Even when pesticides can be used, the longer periods of storage raise problems of the preservation of quality without increasing chemical residues to unacceptable levels.

In the humid tropics there are major problems in maintaining quality because of the high moisture content of grain, particularly during the wet season. Traders and millers in the private sector may procure grains during the period of the year when they can benefit most from sun drying, but during the wet season they may stop buying and farmers then have to divert their wet crops to the central grain-handling organisation.

There is no single solution to these problems and bulk storage provided with aeration and drying facilities is likely to be but one of the alternatives that can be applied as appropriate to a particular situation. The potential benefits of bulk storage and the use of aeration and in-store drying in maintaining grain quality have been described in earlier papers. The establishment of a bulk storage and handling system provided with aeration or drying facilities may show, prima facie, little advantage over seasonal bag storage systems in developing countries where in most cases absolute control of insects is not essential and where few moisture problems arise. Loss-assessment studies could be conducted to establish more precisely the benefits of the new system over the existing one by taking account of quality parameters such as percentage of discoloured grains, extent of mould damage, proportion of broken grains, and milling yields (of rice). However, we must guard against objectivity becoming confused. Loss assessment is not advisedly used to justify a change of technique under the guise of loss reduction when the real motive may be higher productivity obtained through labour or capital costs.

The loss prevention technique may lead to a significant increase in food availability (the prime aim of loss assessment/loss reduction programs), but it may achieve improvements in quality as mentioned above. Once again, care is needed in interpreting the benefit. The value of the new technique may actually be in raising the quality rather than reducing a loss. The conventional quality standards, particularly those of industrialised countries, if applied here may not be appropriate and due consideration must be given to local perception of quality. The real value of this 'improved' quality will depend upon the extent to which it is appreciated by the consumer.

Both quantitative and qualitative deteriorations occur in the humid tropics because of the high moisture content at harvest time. If wet paddy is taken into store, mould, germination, and yellowing of the rice will occur and so the need to dry the grain is obvious.

There is a widely held view that yellowing and discoloration arises only in store and that aeration and drying may well be the answer to the problem. However, studies of simulated postproduction processes made by Mendoza et al. (1981) and Mendoza and Rigor (1981) demonstrated that, at the field level, the combined effects of ambient conditions and biological factors determine how long paddy can be left unthreshed before deterioration reaches unacceptable levels. A delay of 5–6 days in threshing wet paddy will result in paddy with darkened or yellowed kernels and a loss of lustre in the rice milled from it.

The introduction of central drying facilities must be carefully considered since the economics of the operation will be dependent upon a supply of paddy which has not already deteriorated. This means that an infrastructure must be developed which allows farmers to bring wet grain to a drying facility quickly.

These examples serve to illustrate the need to view postharvest problems as part of a total system rather than in isolation.

Marketing Organisations

There are several reasons why marketing organisations need to store cereal grains. These include: (a) the storage of seasonal or operational stocks to meet seasonal demands and to stabilise prices; (b) the maintenance of a carry-over stock between seasons, and (c) establishment of a strategic or long-term reserve against crop failure. In every case, the marketing policy of the government will determine the scope and scale of operations. Seasonal and carry-over storage involves the collection of locally procured produce, usually into stores holding 1000 tonnes or more, and storing it for periods of up to 12 months, although longer storage of 18–24 months is not uncommon.

Deterioration during storage can be limited by ensuring that the produce received is in good condition and sufficiently dry to prevent spoilage by moisture, and through good storage management embracing a high standard of store hygiene and the use of insecticides and fumigants to control insect pests.

The efficiency of the various storage operations has not been the subject of intensive comparative study. However, it is apparent that it varies widely from good to poor, with losses ranging from small to complete. These losses will arise from the activities of, for example, insects, rodents, and birds, and the growth of microorganisms. Further losses will arise through spillage, breakage, etc., but it must be recognised that the root cause of the problem may be deficiencies of management or policy.

It can be argued that the approach to loss assessment and loss reduction has been largely symptomatic. An individual may identify the primary constraint in terms of his own discipline. An engineer, for example, may view the solution of postharvest problems in terms of a need for better grain stores or drying facilities. The entomologist, on the other hand, may see it in terms of insect pest control, while the economist may view the problem in terms of the need for credit facilities. All may be important, but so will many other views. No single approach can be considered in isolation from the system.

As a result of experiences of loss-assessment studies, a multi-disciplinary approach to removing some of the constraints has been developed. Nevertheless, in relation to the commercial sector, this approach has tended to concentrate upon technical site management with little attention to broader issues. The systematic approach implies studying the system as it exists, then devising, as a concept, the perfect system, i.e. one which is free from constraints. This may be too idealised, but one can determine the important constraints that can be removed and how best to do that, thereby arriving at a pragmatic system which, though still not perfect, is significantly better than what exists.

Marketing organisations accept some operating losses within varying limits as part of their overall running costs, but the losses are frequently poorly defined. The difficulty arises because the organisations cannot quantify grain movements in sufficiently precise terms to enable them to identify normal operating losses and losses which are preventable, e.g. caused by insects, moulds, etc. The overall level of loss accepted in marketing board operations may be arbitrarily fixed at one or two per cent of grain tonnage or value. Resources are committed to limit loss and to maintain grain quality, but often without a full analysis of cost effectiveness. It is therefore necessary to take account of not only stock losses but also the multitude of problems due to inefficiencies, overreaching of staff and management capability, inappropriate or inadequate facilities, ill-defined or inappropriate policies (for prices, stockholding, reserves, etc.), inadequate technical procedures, and inadequate crop and market intelligence. Any of these factors, alone or in combination, will give rise to low levels of cost effectiveness.

Research Needs

The improvement of design and operating efficiency which will lead to a better understanding of acceptable levels of operating losses might be achieved by the application of systems analysis techniques. Such an approach requires the construction and operation of simulation models to test the implications of various system designs and operating procedures. It would assist in national planning of new systems for marketing organisations (i.e., to ensure optimal allocation of resources for collection, drying, storage, distribution, etc.) and it would enable the identification of constraints in existing systems and possible remedial measures.

There is a need, first of all, to develop basic models for specific (one country) systems, and later to test and adapt the models to other systems in other countries. Experience in this field is limited; however, some progress is being made in Indonesia through a joint National Logistics Agency (BULOG)/U.K. Tropical Development and Research Institute study of minimum stock reserves. The study is concerned with food security in Indonesia, the role that BULOG plays in ensuring adequate food supplies, and the requirements (in terms of grain stocks and stock locations) necessary for BULOG to carry out its role efficiently. The objectives are to assess what decisions BULOG should make to ensure an adequate level of food security, faced as it is with changing levels of production, demand, government policies, and other factors outside its control.

Econometrics and linear programming are methodologies which have been applied to grain marketing problems elsewhere but the study in Indonesia is innovative in the way these two methodologies are used in a closely integrated manner to analyse the problems facing a food grain intervention agency. To date a set of working models has been developed and these have been shown to be capable of providing guidance on minimum stock levels at distribution points and the lowest-cost ways of moving them. However, considerable improvement and further development is needed to relate them more precisely to market conditions.

This experience is related primarily to stockholding and distribution but parameters for spoilage, methods and costs of operating various storage and handling systems, loss reduction methods, and different climatic conditions might be utilised at some stage in a basic data bank which can be drawn upon in developing future models.

This approach to 'loss assessment' is far removed from the farm level studies, the studies of specific parts or problems within the system, and those designed to evaluate a particular intervention method. All are important but we must recognise that the loss assessment activity over the past decade has not led to the widespread increases in available food that were expected. It is undeniable that action is urgently required to improve conditions in the postharvest sector and it is perhaps appropriate to look at this need in the global context. Over the decade 1970–1980, world food output per capita rose by about 0.5% [1.1% for industrial market economies; 1.4% for South Asia (Anon. 1978).)] While this rise may be taken to indicate the success of policies and technological developments aimed at increasing production, a further breakdown of the figures reveals the disturbing fact that production in the African continent actually fell by 1.1% over the period. In many African countries, physical losses of grain quality and quantity were overshadowed by various perturbations. The fall in production is in part attributable to natural disasters, e.g. the Sahelian drought, but other factors such as political instability and the insecurity caused by guerrilla activities have seriously disrupted the production, storage, and distribution of grain stocks. Added to this, a depressed world economy has hit agricultural production and distribution through shortage of currency and credit, high prices of essential inputs (fertilisers, pesticides, fuels, etc.), and weakened transport infrasture.

The real priority for governments is to face up to the need to apply integrated policies of food production, marketing, storage, and distribution. Given the present difficulties, there is a special need for assistance to enable governments to make the most effective use of the resources available to ensure that the maximum amount of produce of the highest acceptable quality reaches the consumer by the most efficient (cost-effective) means.

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The Economics of Grain Drying in the Humid Tropics

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Abstract

A model which can be used to appraise alternative drying technologies is developed. The equilibrium or economic optimum level of drying operations is defined in terms of the economic threshold of moisture content below which point further drying reduces farmer's net returns. Economic optimum levels of drying depend on a number of critical parameters including time, quantity dried, rate of moisture content reduction, qualitative changes in the grain, as well as drying costs and anticipated returns. The paper concludes by discussing the linkages between drying operations and other postharvest operations of transport, storage, milling, and distribution, and the necessity of a systems approach to arrive at the most socially efficient pattern of drying facilities.

DRYING of grain in storage is done for a number of reasons, including preservation of grain quality, reduction of pests as part of an integrated pest management system, and to achieve a higher price for the stored product. Other indirect benefits include timely early harvests which allow better utilisation of harvesting equipment. Losses in yield in terms of both physical and qualitative loss are largely dependent upon the storage environment. If the product is not stored at a 'safe' level of moisture content then deterioration and spoilage occurs.

Drying and aeration procedures are part of the storage and inventory considerations made by all those involved in the marketing chain including farmers, grain handlers, processors, and wholesaler/retailers. Each of these agents in the marketing chain may adopt different attitudes to determine whether drying is of personal economic benefit. However, the actions of each individual agent together determine the net benefit from drying to society as a whole.

In this systems framework the main issues relate to the type, location, number, and size of drying outlets. For example, net social welfare may be maximised with a pattern of small size, decentralised drying facilities at farm level which, although operating at higher cost, are of greater benefit than investment in large-scale facilities which have lower operating cost but are offset by higher assembly costs (queuing, transport, and delays in the system).

In terms of paddy pricing policy, there may be little or no incentive to dry the product if the full subsequent resource costs of drying are not passed on to the farmer in terms of a premium[1]. Consequently, drying and aeration have important implications on policy issues relating to paddy and rice pricing systems.

In summary, there are three key issues regarding drying and aeration which I think economists have an important role in resolving. These issues are:

(1) at the level of the individual decision maker — what is the conceptual framework for determining economic threshold levels of drying?

(2) at the industry level — what is the appropriate framework for determining the type, size, number, and location of dryers? and

(3) at the national level — what is the impact of alternative pricing policies for paddy and rice on drying and aeration procedures?

In the next and subsequent sections these issues are addressed by first developing a conceptual framework in which economic analyses can be made.

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[1] It is usual to find that discounts or penalty charges for high moisture grain are less than actual drying costs because buyers of grain have the facility to blend high moisture grain with dry grain.

The Economic Threshold Level of Drying

From the viewpoint of any individual economic agent (farmer, miller, or trader) drying is of economic benefit if the returns in terms of price premium per unit are sufficient to offset the costs of drying[2]. The economic threshold level of drying is the point below which further drying reduces profits. This concept was recently applied by Chew and Loo (1985).

The economic threshold level of drying recognises that there may be a level of moisture content above the technically defined 'safe level'. The latter, however, only results in reduced profits compared with the economic threshold level.

To express the concept of the economic threshold level of drying in mathematical and perhaps more operational form consider the following model cast in terms of the individual farmer as decision-maker.

$$\pi = P_y Y - C \qquad (1)$$

where

π = profit per tonne of paddy to the farmer;
P_y = net return per tonne of rice;
Y = quantity of head rice recovered per tonne of paddy, expressed as a percentage;
C = cost per tonne of drying paddy.

The head yield of rice or recovery rate Y can be expressed in terms of moisture content (m.c.), x, as follows:

$$Y = f(x). \qquad (2)$$

Similarly, the cost per tonne of drying paddy depends on the hours (H) spent drying, which can also be expressed in terms of final m.c., x.

$$H = g(x) = > C = g(x). \qquad (3)$$

Substituting these relationships in (1), the optimum m.c., x, can be determined as:

$$\frac{\partial \Pi}{\partial x} = P_y \frac{\partial f(x)}{\partial x} - \frac{\partial g(x)}{\partial x} = 0. \qquad (4)$$

[2] The costs and benefits of grain drying arise throughout the entire life of the system so that an economic evaluation of the system should incorporate all cash flows over its lifetime. Further, since money has a time value, all the cash flows must be discounted to present value terms. For exposition purposes we assume that all returns and costs have been discounted.

The forms of the functions f(x) and g(x) are such that

$$\frac{\partial f}{\partial x} \leqslant 0 \text{ and } \frac{\partial^2 f(x)}{\partial x} > 0 \text{ while}$$

$$\frac{\partial g}{\partial x} \leqslant 0 \text{ and } \frac{\partial^2 f}{\partial x} > 0$$

The relationships involved are drawn in Figure 1. These relationships show that recovery rate and cost are inversely related to m.c., x.

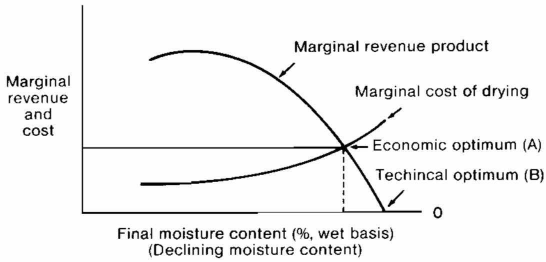

Fig. 1 Comparison of economic and technical optimum levels of grain drying.

Using (4) it is possible to make some inferences about the economic threshold level of drying relative to the technical optimum.

The technical optimum is the point at which the first derivative of head rice yield with respect to m.c. is zero. This occurs at B in Figure 1, the level of m.c. at which head yield is maximised. The economic threshold level of drying in terms of m.c. lies to the left of the technical optimum at a higher m.c. since extra drying can never be without cost. The difference between the technical and economic threshold level of m.c. depends on the relative slopes of the drying and yield functions. Some empirical evidence suggests that marginal revenues may decline sharply while marginal costs from extra drying may rise gradually at or near the point of intersection[3].

The economic threshold level of drying will increase as marginal costs of drying increase at constant marginal revenues and the level will also increase as marginal revenues are reduced. Profit to the farmer will also be maximised if drying facilities are used in this way.

The conceptual framework described above assumes that the farmer has already installed

[3] Fredericks and Wells (1983, p. 73 et seq.) provide some evidence on drying costs and yields.

drying facilities and that these are in operation. The decision to invest in drying facilities is of a much longer-term nature, implying that the returns from drying are sufficient to pay for depreciation and interest on capital invested, as well as giving a return for management. For example, if the net return from drying is $2 after deducting operating expenses then, at an interest rate of 10%, up to $20 per tonne can be invested in drying facilities for this rate of interest. At higher interest rates, the level of investment is reduced. The implications are that determination of economic thresholds for drying, and decisions to invest in drying facilities are interrelated, in that short-run operational decisions determine longer-run, break-even levels of investment in drying facilities. This conceptual framework also provides a means of evaluating choices among alternative drying strategies.

Applied studies in the provision of drying facilities are usually conducted in the framework of conventional, cash-flow investment analysis [see, for example, Kwon (1980); Kwon and Catania (1980); Fris and Manilay (1984)]. Economic evaluation is easily made in terms of comparing the present value of benefits (B),

$$\sum_{n}\left(\frac{1}{1+i}\right)^{n} B_{n} \quad \text{with costs, (C),} \quad \sum_{n}\left(\frac{1}{1+i}\right)^{n} C_{n}$$

for period, n, or determining the internal rate of return (IRR) or the interest rate, i, at which

$$\sum_{n}\frac{(B_{n}-C_{n})}{(1+i)^{n}}=0$$

In the latter analysis, taxes, interest on capital, and depreciation are not deducted from the benefits stream as these are considered transfer payments within society. Thus, the IRR represents the average earning power of the project that benefits society as a whole.

These financial analyses, evaluate whether investment in a drying facility is economic. They do not provide any guidance on the issue of what should be the optimum level of drying and investment in drying facilities.

Determination of the Optimal Pattern of Drying Facilities

The choice of location, size, number, and type of drying facilities depends on a number of factors including the assembly cost of the material at each proposed location, the cost of drying, the distribution cost of dried material to subsequent processes in the marketing chain, and the opportunity to increase net industry returns from drying. In terms of locational advantage a large integrated drying storage and milling plant may certainly reduce the costs of drying through economies in size and distribution costs after drying, but these cost savings have to be balanced against the increase in assembly costs (transport costs to the integrated complex and queuing) as well as the possibility of deterioration in value of the product stemming from increased delays before drying commences.

The pattern of industry organisation of drying facilities which emerges from this scenario is a tendency towards a concentration of facilities in which the cost saved from increased throughput offsets the other cost/revenue disadvantages.

On the other hand, a fragmented industry organisation of drying facilities would suggest that industry returns would be increased from a larger number of smaller size dryers. Although more costly to operate than larger facilities, they enable the product to be dried more rapidly thereby reducing spoilage as well as assembly costs.

The optimal configuration is obviously a balance of these two extreme cases. In addition, the fact that there are dryers already in existence some at farm, village, or large integrated complexes also implies that for planning purposes the investment in these facilities can be regarded as sunk costs. Here the main issue is whether facilities should be expanded or rationalised and, if so, what should be their size, number, location, and type. This is the approach we are currently taking in ACIAR Project 8344 (Ryland and Hansen 1985).

There have been a number of applied studies in this field of research. Candler et al. (1972) considered a ricemill locational problem involving the least cost allocation of paddy from 49 dryers to 16 mills in which all 16 mills had the same non-linear (concave) cost function. The optimal solution indicated that 7 mills could be closed and showed that falling average costs of milling and drying associated with large volumes more than offset the increase in transport costs associated with fewer mills.

A study by Soo Lip Tan (1971) considered the least-cost location pattern of drying facilities given 38 assembly points for paddy in the MUDA irrigated rice-growing region of Malaysia. The optimal least-cost pattern depended heavily on availabilities of paddy, with number of dryers increasing with quantity of paddy available. This would seem to indicate a tendency towards a dispersed pattern of industry organisation. Unfortunately, the available literature does not provide any analysis of situations which deal with optimal size, number, and location of mills and dryers simultaneously. One of the aims of the present ACIAR project on bulk handling in Malaysia is to develop a model which provides a simultaneous solution to this issue as well as analysing the impacts of alternative transportation and handling technologies.

The Bearing of Drying on Paddy Pricing Policies

The choice of type, location, number, and size of drying facilities, investment in drying facilities, and operational strategies for drying may be made more complex by a grading system for paddy in which differences in paddy prices based on quality differences do not accurately reflect milling efficiency and the resource costs involved in milling and marketing of rice. An improved grading system for paddy would provide the necessary incentives for farmers to receive a price for paddy which reflects the full resource costs in improved milling efficiency. The main problem, at least with the Malaysian system, is that current discounts are insufficient to compensate millers for processing paddy of lower quality.

This means that the returns to the miller are insufficient to compensate for the extra costs involved in milling lower quality paddy. What is required is a reduced number of broader quality classes with larger price differentials sufficient to provide adequate compensation for the miller as well as providing incentive to the farmers to improve paddy quality.

While the extent of paddy price subsidy may itself be inefficient in terms of resource use, the main focus here is the efficiency of the existing grading system for paddy in providing a system of returns to the farmer which provides him with sufficient incentive to invest in drying facilities, the benefits of which are passed on to the miller in terms of increased milling efficiency. The increased returns to the miller should be sufficient to compensate him for the increased price of paddy.

In order to develop an improved grading system for paddy, there are a number of areas which require further research. These include the development of milling and drying cost functions which include quality parameters so that the relationships between cost and quality can be better understood (Fredericks and Wells 1983). There also needs to be further work on the relationship between milling efficiency and quality as there is a paucity of published information in this area, particularly in relation to observations on higher moisture contents.

Areas for Future Research

Economists have a vital role to play in collaborating with engineers and biologists to indicate the deficiency of existing experimental results, some of which cannot be used to provide the information base necessary for economic analysis. In particular, there appears to be a lack of information relating milling efficiency in terms of head rice yield with measurable quality parameters such as moisture content, broken grains, immature grains, and yellowing. There is also a lack of technical information on the extent to which drying can be used as a substitute for pesticide application. Consequently, there needs to be additional work on the relationship of pest population levels, pesticide use, and drying.

In terms of cost functions, the economist can contribute by analysing the behaviour of drying costs with increased quality so that the extra costs associated with quality improvement can be determined. The latter will provide a basis for determining economic threshold levels of drying and for analysing alternative grading systems.

Finally, economists, engineers, and biologists should elicit the support of system scientists so that the issue of paddy transport, drying, storing, milling, and distribution of rice can be analysed as an interdependent system in which all activities in the marketing chain are examined simultaneously. There are probably considerable potential research benefits stemming from a holistic view of drying and aeration procedures rather than analysing this area in isolation.

The main benefits of each of these areas will probably be gained more from changes in paddy pricing structures than from changes in current drying and aeration procedures.

Concluding Remarks

In this paper I have identified three issues and avenues of research where I believe the economist can contribute either individually or in collaboration with engineers, biologists, or systems scientists. Drying and aeration procedures are operations which should be considered along with general inventory considerations of the farmer, processor, or trader. It is important that drying should be considered simultaneously with transporting the raw farm product, storing it, and transforming the raw product into a final product. The benefits from drying in terms of increased return to the economic agent can only be economic if they are sufficient to offset the extra costs involved. However, full benefits from drying may also include some indirect benefits in terms of less spoilage due to lower pest and disease incidence, while indirect costs could mean an increase in pollution through increased energy use. This means that drying itself may also have some indirect social welfare benefits as well as costs. Drying is only worthwhile if net social welfare is increased.

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Some Economic Aspects of Drying of Paddy by Farmers in Selangor, Malaysia

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Abstract

A serious problem in Malaysia, which causes large postharvest losses, is the high moisture content of paddy delivered to National Padi and Rice Authority (LPN) complexes. A simple analysis, involving assessment of returns from versus costs of drying, is used to explain why farmers do not dry their paddy. The analysis is based on the existing paddy pricing system. Two characteristics of paddy loads resulting from the analysis are examined against a random sample of data, obtained from two government complexes, on paddy moisture deductions. Some changes to the existing paddy pricing systems, including a method for deriving 'fair' moisture deductions, are suggested.

A factor contributing to high post-harvest losses in Malaysia is the high moisture content of paddy sold to Lembaga Padi dan Beras Negara (LPN; National Padi and Rice Authority) procurement centres. These government-owned centres, which may incorporate paddy processing complexes, were set up to help rice growers market their crop. They act as a buyer of last resort; i.e. they cannot reject paddy brought in by farmers, although certain deductions are made for dirt, broken or immature grains, and excessive moisture content.

Under the present system, there is no incentive for farmers to dry their paddy. Given that the government intervenes in the paddy market through its input and product subsidy schemes, the question arises as to why incentives are not introduced into the paddy pricing system. This paper compares the costs and returns to a paddy farmer of drying his paddy with the costs and returns of not doing so. It is established that the present paddy pricing system, which includes both grading and deductions for excessive moisture, provides no incentive for paddy drying. Two characteristics of paddy loads that follow from this are examined, using a random sample of data on paddy received at two LPN complexes. Certain changes to the existing paddy pricing system, including a method for deriving 'fair' deductions for moisture content, are suggested. Some brief policy implications are also discussed.

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The Current Paddy Pricing System at LPN Centres

LPN pays farmers the following rates for 100 kg of paddy:

long-grained	\$49.61[1]
medium-grained	\$46.30
subsidy	\$16.54.

The rates are for grain at 14% moisture content (m.c.). Deductions are made for moisture contents higher than 14%, as well as for dirt and broken or immature grain. Table 1 shows the actual moisture deductions made (column 2)[2] for paddy at various moisture levels (column 3) for a random sample of 232 deliveries of paddy. The data were obtained from LPN complexes in Sekinchan and Sungai Besar for their most recent paddy receivals.

Column 1 lists increasing moisture deduction for calculating the value of paddy, after deduction, shown in column 4. Column 5 shows the 'loss' suffered by farmers as a result of moisture deductions. From society's viewpoint, it is not a 'loss' at all as the column is simply a record of moisture in the paddy.

We can compare returns with and without drying as follows:

[1] All prices are in Malaysian Ringgit: \$M2.4 = US\$1.

[2] The subsidy and paddy prices are based on grain at 14% m.c. In the actual computation of moisture deduction based on gross weight, i.e. weight of paddy plus weight of gunny sacks, a base rate of 12% m.c. seems to be used.

Table 1. Returns[a] from 1000 kg paddy (gross weight)[b] at various moisture deductions

Increasing deductions (theoretical only) (%)	Actual deduction from LPN data (%)	Moisture levels in paddy (%)	Value of paddy after deductions ($)	'Loss' due to deductions ($)	Column 4 + Column 5 ($)
0	no cases	12–13	628.400	0	628.400
1	no cases	13–14	622.116	6.284	628.400
2	given 1%	14–15	615.832	12.568	628.400
3	no cases in data	15–16	609.548	18.852	628.400
4	4	16–17	603.264	25.136	628.400
5	5	17–18	596.980	31.420	628.400
6	6	18–19	590.696	37.704	628.400
7	7	19–20	548.412	43.988	628.400
8	8	20–21	578.128	50.272	628.400
9	9	21–22	571.844	56.556	628.400
10	given 10.5	22–23	565.560	62.840	628.400
11	given 11.5	23–24	559.276	69.124	628.400
12	given 13	24–25	552.992	75.408	628.400
13	no cases in data	25–26	546.708	81.692	628.400
14	no cases in data	26–27	540.424	87.976	628.400
15	no cases in data	27–28	524.140	94.260	628.400

[a] Prices are in Malaysian Ringgit: $M2.4 = US$1.
[b] Gross weight refers to weight of paddy plus weight of gunny sacks. Some minor adjustments would have to be made in columns 4, 5, and 6, if weights of gunny sacks were excluded. The actual moisture deductions, as shown in LPN records, were made in terms of the gross weight.

with no drying, revenue $= (Y_w - D)\, P_{dp}$ (1)

with drying, revenue $= (Y_w - L)\, P_{dp} - K$ (2)

where

- Y_w is weight of wet paddy, say 1000 kg;
- D is deduction for moisture, converted to kg;
- L is weight loss in paddy from drying;
- P_{dp} is price per unit weight of 'dry paddy' (14% m.c.) inclusive of paddy subsidy;
- K is cost of drying, including the opportunity cost of time of the farmer or his agent.

The variables that LPN can manipulate, to induce paddy drying are D and K. L, the weight loss from drying, is a technological constant. Farmers would have an incentive to dry their paddy only if

$$(Y_w - L)\, P_{dp} - K > (Y_w - D)\, P_{dp} \quad (3)$$

or

$$(Y_w - L)\, P_{dp} - (Y_w - D)\, P_{dp} > K \quad (4)$$

or

$$DP_{dp} > (K + LP_{dp}). \quad (5)$$

In addition, to ensure that the incentive to dry is much greater at high paddy moisture levels (say, over 25%) compared with low moisture levels (say, below 20%), LPN should ensure $DP_{dp} \gg (K + LP_{dp})$ at high paddy moisture levels. We can look at our LPN data to see if equation (5) is satisfied and also if there is a difference in incentive to dry at high compared with low moisture levels.

Is there an Incentive to Dry [$DP_{dp} > (K + LP_{dp})$]?

As an example, we look at the case of a farmer who delivers 1000 kg of paddy at 21%–22% m.c. He is given a moisture deduction of 9%, equivalent to $56.56 (Table 1). If the farmer were to dry his 1000 kg of paddy to 14% m.c., he suffers a weight reduction of about 81.4 kg[3], which is equivalent to $51.15. Thus, the farmer would only dry his paddy if K were less than $5.41 ($56.56–$51.15). Another way of looking at the situation is to say that $571.84 (Table 1) is the value the farmer gets for his paddy without drying. If the farmer were to dry his paddy from 21% m.c. to 14% m.c., his 1000 kg eventually reduces to 918.6 kg which is worth $577.25. He gains

[3] The weight reduction is derived from the definition of paddy moisture content given as

$$\%\ \text{m.c.} = \left(\frac{M}{D + M}\right) 100$$

where M is weight of moisture, and D is weight of paddy dry matter.

(577.25–571.84) dollars or \$5.41[4] as before, which would hardly cover K, the cost of drying, given that the daily wage for a casual labourer is around \$12.00.

Similar computations for other paddy moisture levels show that equation (5) is not satisfied.

A characteristic of paddy loads that would follow from the fact that there is no incentive for drying, would be a 'bunching' of paddy moisture levels around a certain level determined by weather and other conditions at harvest. If, on the other hand, the incentive for drying is present, there would be a greater distribution of moisture levels, including many deliveries of lower moisture content paddy. Table 2 confirms the preponderance of cases of paddy loads around 20% m.c. (i.e. for moisture deductions of about 9%) in our random sample.

Incentive to Dry at High Versus Low Moisture Levels

Table 1 shows some slight difference in the incentive to dry paddy at low compared with high moisture levels. At 14%–15% m.c. (gross weight of paddy), to be consistent with other deductions, a deduction of 2% should be made, but LPN data show a moisture deduction of only 1%. On the other hand, at 24%–25% m.c. an actual deduction of 13% was made, whereas it should be 12% in a consistent system. In other words, the present paddy pricing system does have higher penalties for grain at higher (over 21% m.c.) moisture levels compared with that at lower moisture levels, which is as it should be. But our contention, to be demonstrated in the next section, is that the additional penalties of 1% point and 0.5% point for 24%–25% m.c. and 22%–24% m.c. respectively, are insufficient to discourage paddy being brought in at these high moisture levels. Given our contention, it follows that the average weights of paddy deliveries at high moisture levels would not differ from those at low moisture levels. If the differential incentive factor is effective, we can argue that deliveries of high moisture paddy would be in small batches not worth the effort of drying, whereas paddy brought in at low moisture levels would be in larger loads. Table 2 shows that the mean weights of paddy delivered at high moisture levels are not significantly different from those at low moisture levels.[5]

Changes to the Present Paddy Pricing System

We suggest changes to the present paddy pricing system in two areas:

i) DP_{dp} be made greater than $(K + LP_{dp})$ so that the incentive for drying is re-established;

Table 2. Different moisture deductions for various loads (LPN data)

Moisture deductions	Number of cases	Mean weight of paddy load (kg)	Mean value of deductions for moisture (\$)
Sekinchan LPN Complex			
6%	1	5 587.91 (0.00)[a]	239.44 (0.00)
7%	12	6 210.82 (1 438.73)	313.834 (72.73)
8%	45	5 522.01 (1 967.14)	323.02 (113.40)
9%	84	4 772.78 (2 101.51)	316.97 (139.56)
10%	3	3 937.40 (2 528.77)	310.096 (199.02)
11%	25	4 371.96 (2 491.98)	362.97 (206.85)
Total	**170**		
Sungai Besar LPN Complex			
1%	1	1 816.20 (0.00)	11.69 (0.00)
4%	1	1 927.20 (0.00)	51.28 (0.00)
5%	19	1 699.64 (1 181.58)	58.35 (40.52)
6%	5	843.36 (732.38)	35.82 (31.69)
7%	7	1 969.63 (1 749.64)	94.95 (83.88)
8%	11	1 501.69 (1 226.34)	86.08 (70.29)
9%	9	2 088.73 (1 044.23)	132.53 (65.70)
10.5%	4	2 002.82 (1 844.20)	145.11 (133.97)
11.5%	4	1 324.48 (1 038.46)	110.40 (85.59)
13%	1	646.92 (0.00)	61.76 (0.00)
Total	**62**		

[a] Values in brackets are standard deviations.

[4] These calculations are not accurate because DP_{dp} is based on gross weight (paddy and gunny sacks) while LP_{dp} is based on net weight (paddy without gunny sacks). It is possible that over certain moisture ranges, D is less than L.

[5] One could argue that since DP_{dp} was shown to be less than $(K + LP_{dp})$ previously, this section is redundant. However, with large paddy loads, DP_{dp} need not be less than $(K + L) P_{dp}$ because of economies of scale in the drying process at certain moisture ranges.

ii) DP_{dp} be made much greater than $(K + LP_{dp})$ at high moisture levels (over, say, 25% m.c.) so that the penalty for not drying at high moisture levels is more severe compared with that at low moisture levels (less than, say, 20% m.c.).

A 'fair' method for deriving D — 'fair' in the sense that it would be determined under free, competitive market conditions — would be as follows:

with no drying, revenue $= Y_w \, r_w \, P_r$

with drying, revenue $= (Y_w - L) r_d \, P_r - K$

where

- Y_w is weight of wet paddy, say 1000 kg;
- r_w is recovery rate of rice from wet paddy;
- P_r is price of rice per kg;
- L is loss in weight due to drying;
- $(Y_w - L)$ is weight of 'dry paddy' (14% m.c.);
- r_d is recovery rate of rice from 'dry paddy';
- K is cost of drying, all costs included.

As before, drying of paddy occurs if

$$(Y_w - L)\, r_d \, P_r - K > Y_w \, r_w \, P_r \qquad (6)$$

$$(Y_w - L)\, r_d \, P_r - Y_w \, r_w \, P_r > K. \qquad (7)$$

We can rewrite (7) as

$$(Y_w - L)\, P_{dp} - Y_w \, P_{wp} > K \qquad (8)$$

where

- P_{dp} is unit price of 'dry paddy' (14% m.c.)
- P_{wp} is unit price of wet paddy

Under free market conditions, we can expect the 'invisible hand' to exert its role and establish the following equality from (7) and (8).

$$\frac{r_d P_r}{P_{dp}} = \frac{r_w P_r}{P_{wp}} \qquad (9)$$

$$\therefore \; \frac{r_d}{r_w} = \frac{P_{dp}}{P_{wp}}. \qquad (10)$$

From (4) earlier

$$(Y_w - L)\, P_{dp} - (Y_w - D)\, P_{dp} > K. \qquad (11)$$

Comparing (8) with (11)

$$(Y_w - D)\, P_{dp} = Y_w \, P_{wp} \qquad (12)$$

$$\therefore \; \frac{P_{dp}}{P_{wp}} = \frac{Y_w}{Y_w - D}. \qquad (13)$$

Since

$$\frac{P_{dp}}{P_{wp}} = \frac{r_d}{r_w} \text{ from (10),}$$

$$\frac{Y_w}{Y_{wp} - D} = \frac{r_d}{r_w}. \qquad (14)$$

Such a moisture deduction based on the rice recovery rates, would be a 'fair' deduction[6]. As an example, let us compute the 'fair' D for paddy at 19% m.c. For paddy at 19% m.c. and 14% m.c., the recovery rates of rice from paddy are 56.62% and 61.67%, respectively (Fredericks and Wells 1983, p. 74). Using equation (14), we get:

$$\frac{Y}{Y - D} = \frac{61.67}{56.62} = 1.0892$$

If $\qquad Y_w = 1000 \text{ kg}$

then $\qquad Y_w - D = \frac{1000}{1.0892} = 918 \text{ kg}$

$\therefore \; D = 1000 - 918 = 82$ kg which is 8% moisture deduction.

The actual deduction, as shown in LPN data (Table 1) for paddy at 19% m.c. is only 7%.[7] This supports our suggestion that DP_{dp} be made greater than $(K + LP_{dp})$, so that the incentive for drying is re-established.

Assuming that the rice recovery rate for paddy over 25% m.c. is 50%, computation of (14) yields an appropriate moisture deduction of about 18.9%. Such a deduction would be above the 14% or 15%

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[6] This assertion is, of course, simplistic. If r_d, r_w, and K are such that $(Y_w - L)\, r_d \, P_r - Y_w \, r_w \, P_r \gg K$, so that there are elements of supernormal profit in the drying activity, then it becomes debatable if D as derived above would still be considered 'fair'.

[7] This is based on gross weight (paddy and gunny sacks). If net weight is used, divergence between our deduction and the LPN deduction would be greater.

currently practiced by LPN (Table 1). This supports our earlier contention that the current penalties for excessive paddy moisture (over, say, 25% m.c.) are not strong enough deterrents.

Application of (14) would result in a paddy pricing system that reflects the underlying technology in rice processing, viz. high moisture deductions at excessive paddy moisture levels to reflect the high marginal product of drying at these levels, and lower moisture deductions to reflect the lower and declining marginal product of drying as we approach 14% m.c. As shown in equation (7), the fundamental variables determining whether or not drying takes place are r_d, r_w and K.L, the weight shrinkage from drying, is a technological constant and P_r, the price of rice, is irrelevant since it appears in both the drying and non-drying components. If plant breeders were to create a 'miracle' paddy where the recovery rates of rice were the same for paddy with different moisture contents, i.e. $r_d = r_w$, then the drying process would become redundant.

If storage is important and necessary and if storage of wet paddy has deleterious effects on recovery rates, then the obvious implication is that deductions for moisture content by LPN will have to be increased further.

Cost of Drying in LPN Complexes

In Peninsular Malaysia, there are four levels which operate independently or in combination to provide paddy drying capacity. The levels are:

(i) on-farm;
(ii) farmer cooperative complexes;
(iii) private complexes;
(iv) LPN (government) complexes.

In Selangor, there is little or no on-farm drying of paddy and most cooperative complexes do not have drying facilities. Almost all drying takes place in complexes owned either by the government or the private sector. It is no accident that drying facilities are currently an integral part of milling complexes because drying is not a remunerative activity under the present LPN pricing system, which would not induce the establishment of a drying capacity separate from the milling facilities. Rather, drying would be regarded as a 'necessary' evil that cannot be avoided in the process of producing rice of acceptable quality. The LPN complexes, being buyers of last resort, set the limits on the paddy moisture deductions that can be made by private individuals. The moisture deductions given by LPN must be very attractive to rice farmers given the burgeoning paddy stocks in LPN storages. Further evidence along this line is the decline in the proportion of paddy handled by private millers, which decreased from 90% in 1974 to 67% in 1983 (Ghaffar and Hassan 1985). Also, from 1981 to 1983, 25 private millers closed down and more private processing centres may cease operation in the near future (LPN 1984). The price of milled rice has been kept constant for more than 10 years while various cost increases have eroded the marketing margin, making rice processing (which includes drying, milling, and distribution) not as remunerative as before. If the present trend continues, we can expect the role of LPN in the paddy market to increase further. A major question is: What is the cost of paddy drying in LPN complexes?

Ghaffar and Hassan (1985) estimated the average cost of drying a tonne of paddy for six LPN complexes (Table 3) as $46.60. If adminis-

Table 3. Drying costs[a] per tonne for six government complexes.

Costs	Location Pasir Putih	Peringat	Ulu Tiram Buruk	Anak Bukit	Bukit Besar	Simpang Lima
Drying Cost	**42.51**	**30.66**	**39.45**	**59.14**	**43.37**	**64.48**
1) Variable Cost	15.31	16.87	17.94	43.14	23.06	33.78
Unloading	3.13	6.05	2.07	10.62	1.09	6.19
Energy	7.88	5.68	11.94	24.16	14.16	18.29
Maintenance	2.22	3.04	2.59	2.82	2.42	5.68
Wages	2.08	2.10	1.34	5.24	5.39	3.62
2) Fixed Cost	27.20	13.79	21.51	16.00	20.31	30.60
Emolument	1.35	2.37	2.39	5.90	2.25	0.37
Travels	—	—	—	—	—	—
Depreciation	25.85	11.42	19.12	10.10	18.06	30.23

Source: Ghaffar and Hassan (1985, p. 18)
[a] Costs are in Malaysian Ringgit: $M2.4 = US$1.

Table 4: Average drying cost[a] per tonne of rice for mechanical dryers, Peninsular Malaysia

Source	Date	Location	Type of dryer and number	Drying cost	Remarks
Wells, Fredericks & Gul	1971	Selangor	Continuous (1) Batch (1)	33.7[1] 26.3	Survey of two mills
Runte et al.	1973	Kedah	Continuous (6) Batch (5)	7.6[2]	Survey of eleven mills

[1] refers to variable drying costs
[2] includes depreciation

Source: Fredericks and Wells (1983, p. 84)
[a] Costs are in Malaysian Ringgit: $M2.4 = US$1.

trative costs are added, the average cost for drying goes up to $69.32. Compared with values quoted in the literature (Table 4), the drying cost in LPN complexes is very high, even allowing for price changes over the years. Therefore, drying in LPN complexes can by no means be considered efficient.

Concluding Remarks

It seems clear that the present LPN paddy pricing system[8] provides no incentives for drying. This conclusion is supported by empirical evidence and theoretical calculations.

Changes in the pricing system along lines suggested, as well as re-establishing incentives for drying, could also have significant effects on existing paddy flows. Instead of paddy being dried at high cost at LPN complexes with strained facilities, it could be dried in numerous homesteads or in private dryers set up by entrepreneurs or farmer cooperatives. This is where supportive efforts in extension services and financial incentives may have to be undertaken (Cardino 1985).

[8] Why this system of paddy pricing was implemented is puzzling. Most likely it arose from the belief (right or wrong) that middlemen were 'exploiting' paddy farmers by making excessive weight deductions for moisture. LPN, in its efforts to counter this 'exploitation', probably developed the current pricing system. It is possible that LPN has other social roles to play besides ensuring the efficient marketing of paddy.

Overall, a diversified system of drying such as this, divorced from milling and distribution, could lead to improvements in the entire paddy production, processing, and distribution system.

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Cost Implications of Implementing Grain Drying Systems

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Abstract

This paper provides an overview of grain drying in the ASEAN region, assessing its importance and giving reasons for the slow adoption of artificial drying technology. It categorises areas where drying is done into small, on-farm level, assembly points, such as cooperatives or grain traders, and government grains complexes. The economic implications of drying operations at these levels are discussed, identifying cost factors for consideration in financial analysis of drying operations.

THE introduction of high-yielding, early maturing rice varieties, coupled with irrigation and other agricultural innovations, have made possible the double cropping of paddy. With this development, significant quantities of paddy produced are being harvested in the wet season straining existing drying and other facilities. Although artificial drying technology has been more or less perfected, there are socio-economic factors affecting its adoption by the farming community. Consequently, farmers are compelled to sell undried paddy at discounted prices or wait for the sun to shine. As wet paddy deteriorates rapidly, heavy postproduction losses are incurred in the ASEAN region.

The adoption of any new technology is a long and complicated process, particularly by traditional and small-scale farmers. It is generally acknowledged that for any group to adopt a certain technology, the proposed alternative must meet the following conditions:

(a) there is a defined need for the technology;
(b) the technology is effective in solving the problem;
(c) the benefits accruing to the users are greater than the cost of the technology as well as the cost of alternative methods.

The parameters for the adoption of the technologies of paddy drying are even more numerous and complicated. Rice being a political commodity, there are policy matters related to paddy subsidies and price structures which may not satisfy purely economic criteria. Furthermore, there are socio-psychological constraints experienced by farmers who for decades have relied on sun drying. Also, the ASEAN rice production sector is generally fragmented, small-scale, labour intensive, and traditional in terms of the level of technology used. All these factors contribute to the slow adoption of artificial drying by small farmers during the wet season.

Artificial drying technologies are considered effective from an engineering point of view and their need has been established. What appears to be a major deterrent in their adoption is related to the economic aspects of artificial drying.

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Paddy Losses during Drying

Paddy postharvest losses in the ASEAN countries are estimated to range from 10 to 37%. They are made up as follows (de Padua 1979):

Harvesting	—	1 to 3%
Handling	—	2 to 7%
Threshing	—	2 to 6%
Drying	—	1 to 5%
Storage	—	2 to 6%
Milling	—	2 to 10%
TOTAL	—	10 to 37%

While losses attributed to drying per se range from only 1 to 5%, a significant portion of the losses incurred in storage and milling is related to drying. Improper drying, especially during the wet season, contributes to losses due to rotting and down-grading of the quality of milled rice as characterised by a high percentage of brokens, discoloration, and mould infestation.

Of the 54.4 Mt of paddy produced in the ASEAN region, approximately 40 to 50% is harvested during the rainy season. This is of great significance, as the traditional sun drying system cannot be relied upon during the rainy season thus generating considerable strain on artificial drying facilities. It is assessed that at the current estimate of 5% loss, 2.7 Mt valued at US$326.4 million (at current prices) are wasted annually.

Losses related to drying are influenced by factors such as postharvest practices, where the drying is done, marketing operations, and other factors related to the physical environment. A JICA study on paddy losses at the farm level in Indonesia indicated 10% quantitative and 4.4% qualitative losses. In the Philippines, an ASEAN Food Handling Project study on various postharvest practices indicated that drying losses could account for reduction of monetary value by 5 to 58% due to yellowing and quality deterioration. A similar magnitude of losses was noted in Thailand where the study correlated losses in storage due to drying practices. In Malaysia, serious drying problems have been reported during the rainy season when delays in delivery to grains complexes (where drying is done) are common and inadequate drying facilities are strained by heavy deliveries of wet paddy. These studies and observations underscore the positive correlation between delays in drying and the level of deterioration of paddy.

In general, drying is undertaken to prevent the germination of seeds and to retain the maximum quality of the grain at moisture levels which do not allow the growth of bacteria and fungi and which retard the development of mites and insects. Under humid tropical conditions, the threshold level for maintaining good paddy quality is estimated at 14% moisture content (m.c.). Drying considerably affects the quality of grains and, hence, their monetary value. The world grains standard attaches value to such physical attributes of grains as colour, texture, wholeness, and purity. All these attributes are, directly or indirectly, influenced by the drying process.

Drying Systems and Operations in ASEAN

In drying, air is used as the medium to conduct heat to the produce, causing water to vaporise; it also conveys moisture away from the drying produce. The moisture-carrying capacity of the air is dependent upon the temperature and increases with a rise in temperature. The capacity of air to remove moisture from produce depends principally upon the relationship between the moisture content of the produce and the relative humidity of the air. These are the basic principles by which natural and artificial drying operate.

There are two methods of drying: natural (sun drying and aeration) and artificial (mechanical). Sun drying is the most widely used, primarily because of its low cost. Some individuals argue that milling quality is better when paddy is sun dried. The fact, however, remains that with increased output during the wet season, sun drying becomes almost ineffective thus compelling the use of artificial dryers if the value of the crop is to be realised.

The artificial drying systems used in the region range from the simple flatbed dryers to the industrial plant-type dryers with sophisticated accessories. The drying systems vary considerably in terms of fuel used, geometric configuration, and accessories installed in conjunction with the dryer. Oil burners and liquefied petroleum gas are used although their rising cost is becoming a deterrent. Currently, efforts are being made to utilise farm by-products and other biodegradable materials as fuel. Efforts are also being made in harnessing wind and solar energies for drying purposes. Dryers with horizontal grain-holding devices can range in capacity from two tonnes in the case of flatbed dryers used on farm to several hundreds of tonnes in the case of in-store deep bins used in industrial complexes. Various sophisticated accessories have been installed in some dryers used in industrial complexes. These accessories may include mechanical loading and unloading systems such as conveyors and elevators, grain cleaning and dust control equipment, weighing devices, temperature monitoring and control panels, and safety equipment.

This paper will focus on the categorisation of dryers used at different levels of operation in paddy postproduction systems. This is primarily due to the stratification of postharvest operations in the ASEAN countries into:

(a) small on-farm operations;
(b) assembly points, such as cooperatives or grain traders; and
(c) government grains complexes.

The second rationale for this classification is the economic implications, which vary greatly between the farm and the grains complex level.

There is a strong correlation between the point of drying and the capacities and sophistication of drying systems used. The most widely used in the region is the batch-type dryer. This has evolved from the UPLB (University of the Philippines at Los Baños) two ton flatbed dryer which had been adapted to suit various needs. At the small farm level, flatbed dryers with capacities ranging from 2 to 4 t are commonly used. Lembaga Padi dan Beras Negara (LPN) has modified this to accommodate 30 t. Similar modifications have also been made by Badan Urusan Logistik (BULOG) in Indonesia, the Thai Agricultural Engineering Division of the Department of Agriculture, and the National Food Authority (NFA) of the Philippines. The LSU continuous-flow dryer with tempering bins and drying capacities of 1 to 5 t/hour is a common fixture in government and large private grains complexes. To some extent, the Kongskilde vertical batch dryer and the Japanese batch type grain recirculating dryer have been used at assembly points and in large grains complexes. Experimental models of solar dryers and vortex wind pumps for in-store drying are being tested at the farm level and at assembly points, respectively.

The investment and operating costs of dryers vary considerably depending largely on capacity, their level of sophistication, and the fuel used.

Studies at NFA have determined the drying costs of various systems, as shown in Table 1.

The drying costs are highly variable among the types of drying systems and between models in a particular type. They range from US$2.40 per tonne using the vortex warehouse dryer, to US$37.64 using the continuous flow Cimbria dryer. Batch drying cost per tonne ranges from US$3.20 for a rice hull fed dryer, to US$15.11 for a Kongskilde dryer. Wide variation is also found with continuous flow dryers, with costs ranging from US$11.80 to US$37.64 per tonne.

Table 1. Comparative drying costs using various systems.

			Cost/t in US$
I.	Sun drying		0.14
II.	Batch drying	112 hours operation	
	– Rice hull fed		3.20
	– Kerosene fed		4.18
	– Kongskilde		15.11
III.	Continuous flow	(600 hours/year operation)	
	– Satake	2.4 t/hour	11.80
	– Woodland	2.0 t/hour	22.14
	– Cimbria	3.0 t/hour	37.64
IV.	Warehouse dryer	From 25 to 14% m.c.	
	– Vortex dryer		2.40

Source: Mangaoang (1984).

Farm-Level Drying

The greatest resistance to artificial drying is understandably at this level of operation. Government programs have generally encouraged the use of small flat-bed dryers compatible with the volume of production in each farm whose size ranges between 0.25 and 3 hectares. Despite the need for dryers at this critical level of operation, the acceptance of farm dryers is abysmally low. The major causes of this situation are:

(a) high acquisition costs beyond the reach of small-scale farmers due to low production volume;
(b) unsatisfactory performance of some drying systems introduced;
(c) lack of technical know-how in dryer operations, resulting in inefficiency and poor milling results;
(d) capacity of dryers incompatible with farm production and other processing equipment; and
(e) the price structure of paddy, which does not seem to reflect adequately the cost of drying.

In the late 1970s, the ASEAN Food Handling Project introduced several units of flat-bed dryers to farmers in Indonesia, Thailand, and Malaysia. Their provision was supported by training and extension in their proper use and maintenance. While the farmers were generally satisfied with the performance of the dryers, there was a strong indication that they would not purchase one, primarily due to high capital and operating costs.

Several studies have indicated that, in present circumstances, artificial drying is uneconomical for the individual farmer. Studies in the Philippines have indicated that even the smallest size of locally produced, proven, and tested engine-powered equipment is quite expensive for a small farmer to acquire, maintain, and operate. A study by Lorenzana and Pablo (1983) indicated that an internal rate of return of 32.2% may be obtained if a dryer is operated for 30–60 days at 10 hours/day. However, some assumptions were considered as idealised and not to reflect actual conditions in accounting for breakdowns, percent downtime, escalating fuel costs, inadequate quantities of produce, and the possibility of sun drying between rainy days.

A 1985 study commissioned by the ASEAN Food Handling Bureau (AFHB) in West and Central Java, Indonesia, indicated that farmers only dry the paddy which they intend to keep for consumption, and sun drying is the only method used. The reason is obvious, because while sun drying is labour intensive, the opportunity cost of labour is low. Farmers, because of low production volume, reported no drying problems, even in the rainy season. Also, under current price structures and standards, the value difference between selling a tonne of paddy at 24% and at 18% m.c. is just US$4.10. When the cost of artificial drying is imputed, the farmer stands to lose.

A similar study conducted in late 1984 by AFHB and the Department of Agricultural Engineering among maize growers in Thailand indicated that artificial drying is hardly worthwhile. At any given time, the price difference between maize at 18% and 24% m.c. is marginally low and is even insufficient to compensate for the weight loss as well as the drying cost. Although there are seasonal price fluctuations, the farmers are not in a position to dry and store maize, as they have to settle their debts with the merchants soon after harvest.

Assembly Points

This level of operation is treated separately from government complexes for economic reasons. While in many cases drying facilities owned by cooperatives and private operators are similar to those used in government complexes, there are distinct differences in economic motivation. As profits or savings are meant to accrue to members, there is a marked consciousness in operating at the least cost or greatest benefit. There is therefore a stronger business orientation in the operations of cooperatives and private concerns. The same is true with farmers' associations whose primary objective for grouping is the minimisation of cost and the increment in benefits for individual members.

A recent study in West and Central Java, Indonesia, noted that hundreds of drying units of the Lister type and locally manufactured flatbed dryers were introduced to KUDs (Village Unit Cooperatives) over the last decade. They were provided on highly concessional terms and, in most cases, the KUDs did not have to bear the capital cost. Some KUDs have stopped using these dryers. The main reason for this is the extremely high operating costs which under the current price structure make drying an uneconomical operation for the KUDs. Table 2 shows the current price levels for paddy at various levels of moisture content. The paddy price structure does not provide any economic incentive for the KUDs to dry their paddy. The cost of drying paddy and its better quality is not reflected in a premium price.

As previous studies have indicated that drying at farm level is not economical under current conditions, attempts have been made to introduce dryers to farmers' groups. A study undertaken over

Table 2. Price[a] of paddy at various levels of moisture content based on price schedules used in 1984 by Village Unit Cooperatives in Indonesia.

Moisture content (%)	Weight of paddy (kg)	Price (Rp/kg)	Amount paid (Rp)	Value of paddy at 14% m.c.	Benefits from drying (Rp)
13.6–14.5	883.7	165.00	145 814	145 814	—
14.6–15.5	895.3	162.07	145 109	145 814	705
15.6–16.5	907.0	159.17	144 363	145 814	1451
16.6–17.5	918.6	156.24	143 523	145 814	2291
17.6–18.5	930.2	153.48	142 772	145 814	3042
18.6–19.5	941.9	150.70	141 938	145 814	3876
19.6–20.5	953.5	147.92	141 040	145 814	4774
20.6–21.5	965.1	145.52	140 444	145 814	5370
21.6–22.5	976.7	143.10	139 772	145 814	6042
22.6–23.5	988.4	140.69	139 054	145 814	6760
23.6–24.5	1,000.0	138.26	138 260	145 814	7554

Source: AFHB (1985).
[a] In Indonesian Rupiah: 12 Rp = US$1

a two year period in the Philippines indicated a 1:4.39 cost-benefit ratio in using the dryer. While this appears encouraging and should in fact influence price policies to reflect a premium for dried paddy, there are doubts about the assumptions used in the 'with' and 'without' project situation. The added value of approximately 30% is almost an impossibility under the normal situation. A small farmer with limited produce will not allow his crop to rot and reach a level where more than 30% of its value is reduced. Also, it is easier to aerate a small amount of paddy when it is raining (and arrest deterioration to a certain extent) and sun dry it later unless the situation is such that it rains continuously for two weeks or so; under these circumstances, the harvest may be totally lost. Also, management costs, which may need to be included in a situation where the costs and benefits are shared by many, should be included.

A study of maize traders (handling 50–50 t/day) conducted by AFHB in Thailand indicated strong interest in artificial drying by maize farmers. Most farmers sell their maize (undried) immediately after harvest due to indebtedness to traders. There may be some benefits from drying and storing, as indicated by the price fluctuations in Table 3. This illustrates that price differences over time could be more important than differences between prices for wet and dry maize at a given time. With a large volume handled at this level of operation, significant benefits could accrue to the traders by a proper timing of sale of maize. This factor could be the main reason for the strong interest in drying by the traders.

Table 3. Prices (THB/kg)[a] for maize at different levels of the marketing chain in Thailand.

	Dec '83	July '84	Aug '84
Farmgate price (shelling by trader)			
– m.c. 25–30%		2.70	2.00
– m.c. 16%	3.00	3.00	2.25
Farmer delivers shelled maize to trader			
– m.c. 25–30%			2.15
– m.c. 16%			2.40
Wholesale price			
– local: m.c. 14.5%			2.70
– Bangkok: m.c. 14.5%			2.90

Source: AFHB (1984).
[a] 25 Thailand baht (THB) = US$1.

Grains Complex Level

These grains complexes are operated by government agencies which have as their primary functions the maintenance of food supply and stabilisation of prices of cereals, particularly paddy and maize. They operate as terminal points for processed grains in particular. They serve as milling, storage, and distribution points for milled rice or transhipment points to other complexes or other countries. There are serious problems at this level of operation primarily influenced by factors such as marketing and price policies, quality standards, and overloading of facilities. The complexes were designed to handle only 10–20% of the national production. Currently, however, they handle much more than this. The reasons for this are many. With reduced activities by grains traders due to their lack of processing facilities, farmers tend to dump their produce on these complexes. The problem is more pronounced during the rainy season as facilities get overloaded with wet paddy. While the private sector may avoid drying problems by simply not buying, government agencies normally do not do this. This is a complicated problem which has been a subject of many discussions in the past and ways are being devised to overcome it.

In government complexes, a combination of the following systems may be used:

(a) bulk aerated bins, used for pre-drying, tempering, and final drying;
(b) aeration of plenum of bag stack;
(c) aeration of bulk paddy contained within walls of bagged paddy;
(d) flash drying;
(e) vortex wind pump machine.

As these facilities are designed to cater for a small volume of national grains production, serious problems in pre-drying and handling of wet grain occur during the wet harvest season. While efforts are being made to solve this problem by increasing drying capacities, increased paddy production and productivity have easily overtaken the improvement made. This problem has tended to be cyclical. It appears that there is a need for decentralisation of processing activities to avoid overloading of the facilities at grains complexes. Decentralisation, however, would require a review and policy re-direction to meet the objectives. Decentralisation would also imply greater participation by traders and farmers. The participation of traders in processing activities would require incentives to make their operation viable. To encourage farmers to undertake partial drying, drying facilities have to be made available and paddy price structures have to reflect the cost of drying as well as premium for better-quality grain. This implies a review of paddy quality grades and standards and the price accorded to them.

Cost Considerations and Implications

Available economic studies on drying tend to have serious weaknesses in quantifying the economic realities of the environment. The cost implications and considerations vary according to the level of operation and, in general, these factors tend to be left out of the analysis of the economic viability of drying systems at different levels.

In general, only direct costs are reflected. Other costs related to the operation of the dryer are sometimes not considered. Often the analysis results in optimistic conclusions. These results are usually the bases for extending the drying technology to the users. But serious errors in the assumptions on costs and returns could lead to erroneous and misleading internal rates of return, benefit/cost ratios, and pay-back periods which are normally used as the bases for investments. As a result, the actual financial performance of drying operation could be much less than that in the projected analysis.

Various factors interact at varying levels due to different environmental realities. Needless to say, the concerns of small farmers differ from those of a merchant or those of a manager of a government grains complex. Assuming that the technology and other aspects have been proven satisfactory, the financial and economic aspects have to be streamlined if they are to be used as bases for recommendations to users. In general, drying cost is calculated as the ratio between the total operating and adjusted capital costs of the dryer and the total capacity of the dryer expressed in tonnes or kilograms. The items normally costed out are:

(a) acquisition cost;
(b) labour;
(c) fuel;
(d) repairs and maintenance.

While these are the obvious costs in drying, there are so-called hidden costs, the nature and magnitude of which vary according to the level of operation.

The process of investing in a dryer, whether a small 2-tonne flatbed dryer or a sophisticated continuous-flow dryer, is particularly difficult and requires careful analysis. The decision to own a dryer usually involves commitment for a considerable time to such liabilities as repayment, maintenance, and capital cost recovery. The decision rests heavily on a careful forecast and examination of detailed assumptions to justify the investment. Consideration should be given to the physical efficiency, throughput, the cost efficiency of the dryer, and the price/quality relationship for paddy.

As drying technologies improve, the emphasis has shifted from product quality and physical efficiency to cost considerations. Practically all types of dryers can now be manufactured in the region. Moreover, the high capital cost of imported drying units is a key consideration. A lower physical efficiency may be accepted for lower capital investment.

The cost of drying varies considerably due to the capital cost, the design of the dryer, fuel used, utilisation rate, drying performance and capacity, and handling methods involved.

Drying Costs at Various Levels of Operation

In this section, an attempt is made to identify factors operating at the various levels but not normally costed.

Farm Level Operations

In analysing the costs and returns of dryer operation at farm level, the following factors should be considered, as they generally affect profitability adversely, thus reducing the benefit to the users:

(a) *Housing for the unit.* Currently available dryers such as the flatbed models are huge in comparison to the farmer's house. Consequently, a shed has to be built and this is an added cost. This expense may not appear much but can amount to a substantial sum within the farmer's cash flow. Also, because this shed is made of light materials, there are relatively heavy maintenance costs associated with it. The opportunity cost to the owner of maintaining the housing should also be reflected as, in general, small farmers tend to subsist on a daily income.

(b) *Cost of money.* The acquistion of drying units is usually done on a hire purchase basis. Practically all studies reflect only the related interest rates charged by financing institutions. Depending on the country and the source of funds, numerous hidden costs are incurred. There are documentation costs, loan application fees, and other bank charges which in some countries make up an additional 50% over the cost of interest on the loan. In addition, as loans are normally not granted upon application, several trips have to be made to the bank which, invariably, is distant from the farm. The cost of travel itself and the opportunity cost associated with travel could be substantial to the farmer.

(c) *Operating costs.* In most ASEAN countries, fluctuations in the prices of fuel and other materials are commonplace. As fuel constitutes a major operating expense, sensitivity analysis should be made and incorporated into the overall financial analysis to safeguard the farmers' interests. This is particularly relevant in the case of paddy whose price is generally controlled. Although the cost of fuel generally follows world market price, domestic taxes make it an expensive commodity.

(d) *Repairs and maintenance.* In most rural areas in ASEAN, the expertise for simple mechanical repairs is usually not available within the village. Mechanics, due to natural business demands, tend to be located in towns. The cost of employing the services of a repairman goes above his fees, as the farmer has to spend time and money for his own and the mechanic's transport.

(e) *Cost of money during operation.* As most small farmers tend to be subsistent from harvest to harvest, there is normally a scarcity of funds before he can sell his harvest. The cost of fuel constitutes 50% of operating costs. As the incentive for drying is to enable him to get a better price, and he has the dryer anyway, the paddy is assumed to be sold after drying. This means that he has to borrow money at normally exorbitant rates of interest to operate the dryer. This constitutes an additional expense.

Assembly Points

At this level of operation, the main concern is cost reduction and profitability. Generally, the volume of grain handled at this level will determine the mode of drying. In Indonesia, the village cooperatives rarely use their artificial dryers and depend heavily on sun drying. This may not be applicable for the Thai maize traders who handle 50 to 150 t/day or for the private paddy merchants handling similar volumes.

At the KUD level in Indonesia, the cost of sun drying is just Rp 2.94 compared with drying by the Lister moisture extraction unit which costs Rp 11.86/kg. Table 4 shows the comparative costs of these two drying systems. The price difference between various moisture content levels at the current pricing system (Table 2) is minimal. Under current price conditions, the maximum incremental price benefit from drying paddy (from 24% to 14% m.c.) is Rp 7.554/kg. With the current direct cost of drying using the Lister drying unit of Rp 11.86, the KUD stands to lose Rp 4.3/kg of paddy. But this does not cover the total losses incurred by the KUD due to mechanical drying. There are other costs to contend with: amortised housing cost for the unit, and repair, maintenance, and management costs.

In larger private sector operations, there are yet further costs to be considered. Before a drying unit is purchased, a feasibility study or at least a comparative financial analysis of various drying types, is made as the basis for decision making. This entails some added cost. When the unit is acquired, the staff have to be trained, and a mechanics pool may be maintained to undertake repairs and maintenance. Apart from the usual operating costs, there are replacement costs for parts that are expected to wear out during the lifetime of the machinery.

Mechanical dryers are a necessity for large-scale paddy middlemen, and the private sector has been successful in making the dryer an asset rather than a liability.

Grains Complexes

In grains complexes operated by the public sector, the drying facilities tend to be a mixture of sun drying, batch dryers, continuous flow dryers, and warehouse type vortex driers. The figures on drying costs in this type of operation are difficult to obtain. The drying system is an integral part of the whole processing complex and the costs of operating the complex are not broken down into the various processes involved. Storage and drying in warehouses are related operations. Furthermore, such information is normally treated as confidential and is not easily accessible.

The direct drying costs are highly variable

Table 4. Comparison of drying costs[a] in Village Unit Cooperatives in Indonesia.

A. Lister Dryer	Rp
Variable Costs	
Diesel 200 L at Rp 245/L	49 000
Kerosene 100 L at Rp 175/L	17 500
Lubrication 2 L at Rp 800/L	1 600
Labour Rp 1500/t	15 000
Maintenance 1.2%/100 hours	12 960
Total variable costs per batch	96 060
Total variable costs per kg	9.61
Fixed Costs	
Depreciation:	
Investment Rp 9.0 million; lifetime 5 years:	
120 batches per year	15 000
Interest:	
20% p.a. over average value of 50% of Rp 9.0 million;	
120 batches per year	7 500
Total fixed costs per batch	22 500
Total fixed costs per kg	2.25
Fixed plus variable cost per kg	11.86

B. Sun Drying	
Variable Costs	
Estimated at Rp 2.00/kg and consists mainly of labour	
Fixed Costs	
Area required: 2 (days) × 65 m² = 130 m²	
Construction costs: Rp 5 000/m²	
Total costs: Rp 650 000	
Depreciation:	
Lifetime 20 years, 180 days per year	180
Interest:	
20% p.a. over average of 50% of Rp 650 000	
180 operating days	360
Maintenance:	
5% per year; 180 operating days	180
Plastic sheets:	
Rp 60 000 to cover 2 t	
270 days useful life	220
Total fixed costs	940

[a] In Indonesian Rupiah: 12 Rp = US$1.

depending on the fixed cost, capacity and drying rates, as well as on operating expenses. The ancillary and hidden costs are similar to those in large, privately operated assembly points, although their magnitudes may differ. Private assemblers operate as business concerns. Government complexes, on the other hand, direct their operations towards political or social goals such as the maintenance of security reserves, food supplies, and price levels. Hence, the operation of a private grains complex cannot be compared with government complexes.

Conclusions

On the basis of currently available information, several conclusions can be drawn regarding drying operations in the ASEAN region. Firstly, it is widely recognised that artificial drying technology has been well developed in engineering terms and efforts are being made to further develop the technology. Secondly, there is the realisation that the technology has not filtered down to the users, particularly at the farm level. While problems are being encountered at all levels of operation, the problems are no longer directed at the technology per se but on matters related to marketing and price policies associated with the standards and grading system, sociological aspects, and other factors related to the adoption of artificial drying systems. These factors all relate to the economics of drying. A review of these factors appears to be necessary if continuing losses due to drying are to be arrested or minimised.

The third point relates to the financial and economic analysis of drying operations. Financial and economic analyses of drying operations are only guides for decision making. Under various conditions, they can be extremely useful as bases for investment decisions. However, under current conditions, the factors affecting drying operations should be looked at more carefully.

In the financial analyses of drying operations, it is well worth noting that the cost components at various levels vary in nature and importance, mainly because the realities in their loci of operation are different. Also, the purposes of drying vary between levels. At the farm level, where the primary concern hinges on increasing incomes, serious consideration should be given to hidden costs as well as the farmer's loss-bearing capacity, in view of his tight cash flow situation.

In the case of private grains handlers where efficiency is the rule and profitability the goal, the problems are different. Cash flow problems are more easily averted. The problem hinges on the continuing search for methods of reducing the cost of operations. This entails finding the most efficient technology, devising streamlined operations and other ways to reduce costs and enhance profitability. It is therefore not surprising that these concerns have been embodied in the goals of leading research and development institutions in developed countries.

While cost reduction and profitability are also guidelines in public sector grain complexes, it should be noted that their primary purposes are the provision of food to the people in times of adversity, protection of both producers and consumers by stockpiling to maintain prices, and the savings on foreign exchange which may be incurred by minimising imports and increasing exports. Given these mandates, the cost of grain drying may not be of primary significance at the grain complex level.

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Economics of Aeration and In-store Drying Session Chairman's Summary

Shaharuddin Hj. Haron*

FOUR papers were presented, one on loss assessment and three on the economics of drying. These four papers represented a change in focus of the seminar, from the mainly engineering aspects of the three previous sessions, to socio-economic considerations.

The first paper, presented by Mr Robin Boxall, generated a great deal of interest. He highlighted several important points on the merit of loss assessment in the developing country context and on the need to use the results obtained from such studies in future planning and development of the grain sector of the country concerned.

On the matter of the methodology of loss assessment, while this is rather well developed at the on-farm level, the same cannot be said for loss assessment in the commercial sector of the grain industry. Mr Boxall suggested that greater savings and faster corrective measures can be implemented from results obtained in surveys of the commercial sector than of the on-farm postharvest sector. This is so because on-farm activities have more complex socio-economic and political implications. The implementation of improvements resulting from findings of a loss assessment survey may well create more imbalances in the system.

Dr G.J. Ryland's paper discussed the model he has developed to determine the equilibrium or economic optimum level of drying under different situations.

He defined the economic optimum level of drying in terms of the economic threshold of moisture content below which point further drying reduces farmers' net returns. Economic optimum levels of drying depend on a number of critical parameters, including time, quantity of grain dried, rate of drying, and qualitative changes in the grain, as well as drying costs and anticipated returns. The model can be used to select the drying system appropriate to particular countries.

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He also discussed the linkages between drying operations and the other postharvest operations of transport, storage, milling, and distribution; and the need for a systems approach to arrive at the most socially efficient pattern of drying facilities.

The third paper, delivered by Dr Chew Teck Ann, discussed a specific case, namely some of the economic aspects of drying of paddy by farmers in Selangor, Malaysia. He stressed that the current situation, in which farmers did not attempt to dry their paddy at all is due to the fact that there is no incentive for them to do so under the current paddy pricing system.

He suggested that the following changes should be made to the present paddy pricing system:

- the penalty (deductions for high moisture grain not dried) should be made greater than the cost of drying and other associated costs borne by a farmer if he were to dry his paddy;
- the penalty should be made relatively greater for higher moisture content paddy (above 25% moisture content) than lower moisture paddy (less than 20%).

He also suggested the use of free market mechanisms to assist in determination of the penalty factor.

The final paper in the session, delivered by Mr Johnson Mercader, looked at the economics of drying in the broader perspective of the ASEAN region. He cited the importance of mechanical drying in the region, especially for the wet season harvest, and explained the reasons for the slow adoption of mechanical/artificial drying technology.

The engineering aspects of drying in ASEAN are already well researched and developed. However, more R & D studies are required on the economic and financial aspects of establishing and operating the technology, especially at the farmer and cooperative level.

This paper also categorised areas where drying is done in the ASEAN countries and explained the characteristics of the various levels, in so far as the difficulties involved in the adoption of dryer technology are concerned. Given the socio-economic and political background, the most promising level for adoption would be the government complexes.

Overall Findings of the Session

1. On loss assessment
   - A multidisciplinary, broad-front approach is needed in any loss assessment exercise.
   - Data obtained need to be used in further planning and development of the grain industry concerned.
2. Economics of drying
   - The model developed on the economic optimisation of drying should be made use of in appraisals of drying systems before selection on the type, size, and location is made.
   - There is an urgent need to include drying incentives in the paddy pricing system.
   - There is also an urgent need to plan and implement more R & D studies related to the economic and financial aspects of the adoption of mechanical dryers at the appropriate level in the ASEAN region.

Case Studies on Aeration and In-store Drying

Silo Storage in Malaysia

K. F. Loo*

Abstract

A major portion of paddy in Malaysia is stored in bulk in National Padi and Rice Authority rice mill complexes. Before storage, the grain is cleaned and mechanically dried to 14% moisture content (wet basis). Bulk storage takes the form of either concrete tower silos or horizontal bulk bins. Tower silos are desirable on account of easier unloading by minimal labour. However, storage problems manifested in various degrees of grain discoloration have been encountered following use of such silos, the severity of the problems being correlated with length of storage.

Studies were carried out to determine the optimum level of aeration for avoiding grain deterioration. Three airflow rates were investigated: 0.03, 0.1, and 0.3 m^3 of ambient air per minute per tonne of dried grain, designated low, medium, and high flow rates. Results of a preliminary trial suggest that for storage periods up to 4 months, aeration at both medium and high flow rates reduces grain discoloration to about 2% and maintains high germination levels.

LIKE most agricultural crops, paddy is harvested during a very short period of time but is confronted with a reasonably constant demand throughout the season. In order to satisfy this demand, it is necessary to store the seasonal surplus and release it over the rest of the year (Wells and Fredericks, 1983). To ensure that the dried paddy is safely stored before milling, the National Paddy and Rice Authority (LPN) has constructed 26 rice mill complexes each with its own bulk storage facilities.

Newly harvested paddy, after cleaning and mechanical drying to 13–14% moisture content (wet basis), is stored in either flat bottom bins or concrete tower silos, depending on the type of storage facility available at a particular complex. The flat bottom bulk bins are equipped with aeration fans (Calverley et al. 1976). The tower silos do not have aeration facilities. Instead, grain turning is relied upon.

It has been observed that grains keep better in the flat bottom bulk bins than in the concrete tower silos. Very little deterioration is observed in grains stored for durations up to a year in the flat bottom bulk bins. On the other hand, grain discoloration has been observed in tower silos after only 2 months of storage. This discoloration is reflected by yellowing of rice kernels, which lowers the value of the grain.

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Grain Discoloration

Yellowing of rice is a common problem in Southeast Asian countries. Recent trials in Indonesia showed that it can occur both during storage and straight after harvest before drying, the latter associated with high moisture and temperature (Phillips et al. 1984). The same observation on yellow kernels was made in the Philippines, when wet paddy was not dried immediately (Mendoza and Quitco 1984). The number of yellow kernels tended to increase as drying was further delayed. Likewise, the rate of increase in yellow kernels was faster in paddy of higher moisture content.

Bramall (1984) found that there are many types of discoloured grain, ranging from the more common yellowed (stack burnt) kernels to bright red, and sometimes black grain. However, only yellowed grain is of primary concern here as other colours are mainly associated with mould spoilage occurring outside the conventional storage. The yellowing of rice is believed to be a form of non-enzymic browning displaying a heat-time relationship, i.e. it develops more rapidly at higher than lower temperatures. The availability of heat from whatever source appears to be the most critical factor.

Mohd. Nour et al. (1983) reviewed earlier studies which indicated that certain storage fungi, in particular the *Penicillium* species, can cause yellow stains on grains. It was further shown that the discoloration of rice in bulk increased with length of storage, moisture content, and activity of storage fungi.

Another possible cause of discoloration in grain during storage is a phenomenon involving enzymic activities which may, when conditions are suitable, bring about a variety of chemico-biological reactions between the chemical constituents of the grains. Linco et al. (1960) observed that, due to enzymic activity, reducing carbohydrates and free amino acids can be formed within the grain. These two elements can interact under poor storage conditions, such as when excessive heat is present, to produce brownish intermediate compounds.

A study by Teter (1979) showed that grain which had a history of grain damage due to drying delay after harvest exhibited higher rates of grain deterioration during subsequent storage.

Typical Behaviour of an Untreated Bulk

There are several views as to the probable cause of heat build-up during storage. These include poor management of the grains and the system, inherent deficiencies in the engineering design of the storage, or a combination of both (Calverley 1977). There are many areas which need study. We need to know, for example, if the grain deterioration is due to moisture migration or seepage of water. However, it is now evident that seepage of rain water through the silo structure is at most a contributing factor, as some covered silos with full weather protection display grain deterioration as severe as that found in open silos.

Heating Due to Infestation

A typical, newly filled silo contains paddy with a moisture content between 13 and 14% (wet basis) which is low enough to suppress microorganisms but not to reduce insect reproduction to negligible levels (Rawnsley 1976). The paddy may be attacked by insect pests harbouring within the storage structure or brought in with the grain. The insect population rapidly increases and the heat produced by the pests causes a local temperature rise, or hot spot. This can lead to migration of moisture to the cooler upper surface, resulting in mould growth there. When the temperature rises to a certain value, it forces the insects to migrate to cooler areas or results in their death. This process will continue until the insects are confined to the grain surface. There, intensive activity may continue indefinitely, the heat produced being readily lost to the atmosphere. Local observations showed that temperature usually increases fairly uniformly throughout the grain bulk.

Moisture Migration

In an insect-free bulk, moisture migration may still occur as a result of transfer by air convection currents and by diffusion towards the cold surface (Burrel 1974). Moisture accumulates at the exposed top surface of a bulk, around the circumference of the silo, resulting in sprouting and mould growth there. At the same time, the migration of moisture by diffusion to other cooler grain layers will again lead to formation of hot spots and support the growth of microorganisms and other pests. Figure 1 illustrates diagrammatically the various transfer processes.

Heat build-up in paddy stored in concrete tower silos in Malaysia has been reported by several LPN complexes. Grain temperature has been observed to rise above 50°C at the hot spots.

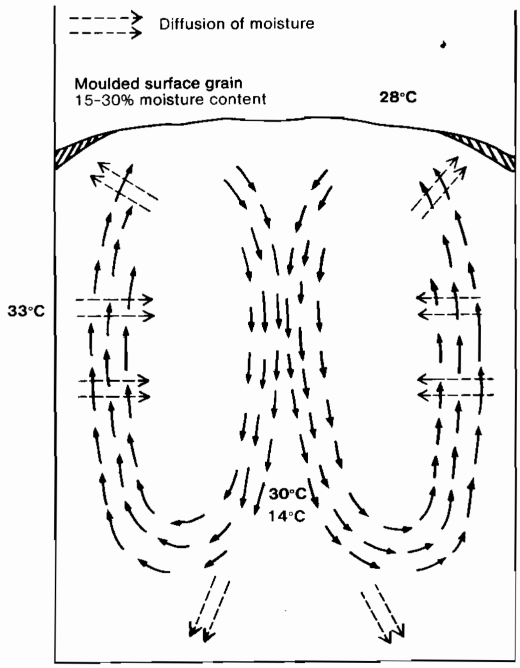

Fig. 1. Pattern of moisture migration to the cold surface of a hot grain bulk.

Control Measures

From the above observations, it appears that methods for controlling deterioration can be broadly classified under two headings (Griffiths 1964).

(i) Chemical methods: the use of insecticides and fumigants to control insects.

(ii) Non-chemical methods: the use of aeration and grain turning in order to control moisture migration and biochemical deterioration.

However, the ensuing discussion focuses on the use of turning and aeration as measures to improve grain storage conditions in LPN complexes.

Turning

Turning is the process of moving grain through air by transferring the contents of a silo into a nearby empty one. The result is a break-up of pockets of insect infestation, a slight loss of heat to the atmosphere, an averaging out of temperature and hence a reduction in maximum temperature, and the mixing of any moist grain with the rest of the bulk.

With the handling facilities available at present, grain turning in LPN silos is a tedious and time-consuming process. A complete turning of 750 t of grain in one silo may take 40 hours and often interferes with other drying and transfer operations of the plant.

Aeration

Aeration is a more convenient strategy in that the grain need not be moved. It is achieved by blowing or drawing air through the grain mass by means of fans (forced ventilation). Normally, the air used in aeration should not only be cooler and drier than the grain to be aerated but also in sufficiently large quantity to achieve maximum effectiveness. In Malaysian conditions, like other parts of the tropics, the ambient air is not suitable for aeration purposes at all times of the day. As a compromise, aeration therefore entails the use of higher air-flow rates at times when ambient conditions are most favourable.

The cost of aeration is by no means negligible and careful design is needed to ensure that a system is as economical as possible. The horsepower and electrical energy costs for aeration rise rapidly with airflow rate and the depth of the grain (Navarro and Calderon 1982; Thorpe 1984). It was precisely for this reason that aeration fans were not installed during the construction of existing silos.

In view of the pressing need for improvement and the attainment of a safe and economical silo storage system, the Malaysian Government, through her agencies LPN and MARDI (Malaysian Agricultural Research and Development Institute), with financial assistance from the ASEAN-Australia Food Handling Programme and technical input from the SEARCA Technical Team, initiated in 1980 a research and development project to incorporate appropriate aeration facilities into the existing silo storage system and evaluate their performances in terms of the following three questions.

(i) Can aeration overcome the problem of moisture migration caused by convection currents?

(ii) What is the minimum airflow rate required and for how long and how frequently has it to be applied?

(iii) What are the limitations of aeration using ambient air during the rainy season when relative humidity is high?

The background to the storage trials, the principles involved, details of method and procedures, analysis of results and discussion of the preliminary findings have been given by Mohd. Nour et al. (1983). Here we review the problems encountered and the findings, and examine possible steps for further development of silo aeration in Malaysia.

Silo Aeration Trials

The LPN rice mill complex at Ulu Tiram Buruk (UTB), Tanjung Karang, Selangor has been selected as the test site. It is situated within the major rice growing area in central Peninsular Malaysia.

The UTB complex has eight cylindrical silos constructed of reinforced concrete. They are arranged in a row and housed within the complex's main building. Each silo is 3.05 m in internal diameter, has a wall thickness of 0.15 m, a height of 25.91 m, and can hold 750 t of paddy at 14% moisture content (wet basis). The silo is capped with a roof slab and protected by a double-pitched asbestos-cement roof. The exposed upper half of silo walls is clad with asbestos-cement. Each silo is self-emptying by means of a conical hopper bottom at a height of 6.10 m above ground. The hopper surface is sloped at an angle of 45°.

For detection of hot spots and grain deterioration, the silo is equipped with 18 temperature sensors (thermistors). There are two sensor cables suspended from the silo top carrying 6 thermistors each. Along the wall, there are another 6 sensors, 3 on each side of the silo diametrically opposite one another. The thermistors are arranged in such a way that each one covers an effective sphere of 4 m diameter. The whole system is monitored at the plant control room.

The silo is also equipped with a vertical bucket elevator for loading and unloading with a capacity of 50 t/hour. A belt conveyor complete with discharge trolley is used for the distribution of grains at the top, while two belt conveyors at the bottom of the silo are used for removal of grain. The hopper is fitted with a remotely controlled, pneumatic shutter gate.

Five of the silos (side by side in a row) were selected for the test. Three of them were equipped with aeration facilities each with a different airflow rate. The remaining two silos acted as the controls involving grain turning from one silo to the other.

Aeration System Selection

The design procedure of Teter (1979, 1982) was adopted to calculate the aeration requirements. Calculations showed that even under suitable conditions of low moisture content of paddy (between 13 and 14%) and normal weather, the minimum airflow rate required is 0.03 $m^3/t/$ minute (Anon. 1979; Rukunudin 1980). The design day selected for normal weather is the maximum and minimum average daily humidity in the wettest month of the year on a 10 year average.

For the first trial, three airflow rates were selected namely: 0.3 (high airflow rate or HFR), 0.1 (medium airflow rate or MFR), and 0.03 (low airflow rate or LFR), the units in each case being $m^3/t/minute$.

The HFR system comprised push and suck cross-flow ventilation. It utilised two 10 horsepower (h.p.) vaneaxial fans, with two vertical perforated semicircular air ducts installed on opposite sides of the internal wall of the silo (Fig. 2a).

The MFR system was made up of a 10 h.p. centrifugal fan running on suction mode. Aeration air was drawn in at the silo top, passed through the bulk mass in vertical ventilation, and was

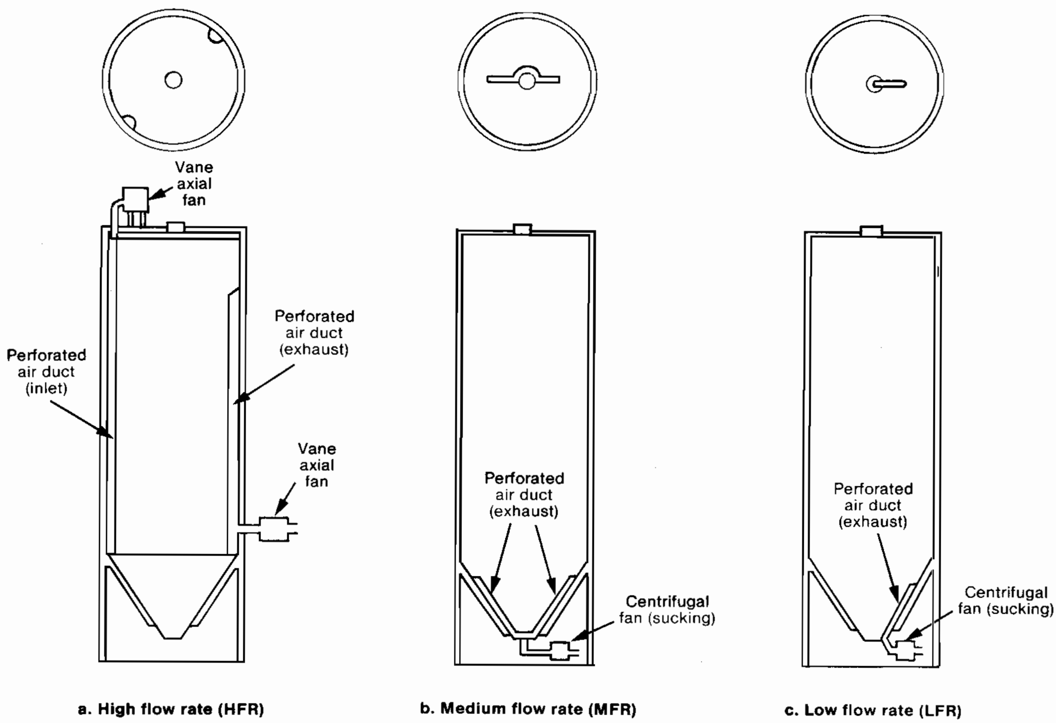

Fig. 2. Plan and elevation of tower silo experimental aeration systems at Ulu Tiram Buruk, Malaysia.

collected at the hopper bottom by means of two perforated semi-circular ducts installed on opposite sides of the sloping surface of the silo hopper bottom (Fig. 2b).

The LFR was similar to the MFR system except that a 0.5 h.p. centrifugal fan was used with a single, semi-circular duct placed radially on the sloping surface of the silo hopper bottom (Fig. 2c).

In all the three cases, the semi-circular air ducts were rolled from perforated steel plate with 39% opening. As noted before, two other silos were reserved for studies on the grain turning system.

Experimental Procedures

The effects of aerated storage at three different airflow rates compared with the control silos for grain turning, were studied for periods up to 4 months in 1981, 1982, and 1983.

Fresh, clean, and dry, good quality long-grain paddy was used in the trial. Efforts were made to ensure that the paddy used to fill all silos was of similar quality.

For complete details of experimental procedures, and an analysis of the results of the storage trials, the reader is referred to the paper Mohd. Nour et al. (1983).

Table 1. Reduction of grain moisture content due to aeration and grain turning.

Treatment	Reduction in moisture content (%, wet basis)
High flow rate (0.3 m^3/minute/t)	0.7
Medium flow rate (0.1 m^3/minute/t)	0.01
Low flow rate (0.03 m^3/minute/t)	1.92
Control (grain turning)	0.75

Source: Mohd. Nour/Jantan et al. (1983)

Review of Findings

The preliminary study of aeration by Mohd. Nour/Jantan et al. (1983) revealed that aerated storage at airflow rates of more than 0.1 m^3/t/minute can reduce yellowing in paddy bulk stored for up to 4 months in concrete tower silos to about 2% (weight ratio of yellow kernels to that of total bulk). There was also a slight drying effect. The results of the study are summarised in Tables 1–5.

The incidence of a low level of discoloured grain as well as localised high temperatures in the grain bulk indicated the presence of uneven air distribution in the aeration system. (The small incidence of yellowing could be due to uneven air distribution which in turn, was due to leakage as well as some duct perforations being closed up by paddy or broken pieces of grain. So, it is evident that fan on blowing mode would be more suitable than suction mode.) For HFR and MFR systems, there was no appreciable change or adverse effect on milling yield, brokens content, hectolitre weight, or germination test, which suggests the absence of widespread insect infestation and microorganism activity.

The study further showed that the energy cost

Table 2. Results of laboratory analysis of grain samples, following aeration at three airflow rates.

Type of analysis	HFR[a]		MFR[b]		LFR[c]		C[d]	
	Before storage	After storage	Before storage	After storage	Before storage	After storage	Before storage	After storage
1. Moisture content (%, oven method)	12.6	11.9	11.96	11.95	11.85	9.93	11.69	10.94
2. Percentage clean paddy	93.9	92.4	97.3	96.5	91.3	93.00	91.5	87.4
3. Hectolitre wt. (kg/HL)	54.5	55.6	55.18	55.91	55.52	54.95	55.05	54.95
4. Milling analysis:								
i. Milling outturn (%)	65.8	64.1	65.2	62.2	66.4	67.7	65.5	63.7
ii. Head rice (%)	67.6	68.6	67.5	63.0	68.6	66.9	69.2	68.5
iii. Broken rice (%)	32.4	31.4	32.5	35.3	31.5	28.9	30.8	28.6
iv. Discoloured grains (%)	0	1.55	0	1.7	0	4.2	0	2.9
v. Husks (%)	34.1	35.9	34.6	36.3	34.5	32.3	34.6	36.3
5. Germination level (%)	91.0	85.1	87.4	89.1	91.0	48.4	86.67	53.3

Source: Mohd. Nour/Jantan et al. (1983)
a. High flow rate 0.3 m^3/minute/t.
b. Medium flow rate, 0.1 m^3/minute/t.
c. Low flow rate, 0.03 m^3/minute/t.
d. Control, grain turning.

Table 3. Actual (commercial level) milled rice yield (%) following aeration of paddy at three airflow rates.

Treatments	A_1	A_2	A_3	A_4	Sample grade	Brokens	Points	Fine bran	Coarse bran	Husks
1. HFR[a] (Silo 26)	6.35	41.65	4.78	—	—	14.15	0.17	11.32	0.68	20.90
2. MFR[b] (Silo 27)	2.21	46.71	2.45	—	—	15.14	0.29	12.40	1.08	19.72
3. LFR[c] (Silo 28)	0.5	36.67	6.53	8.86	8.80	6.28	0.27	12.02	0.99	19.08
4. C[d] (Silo 29/30)	—	—	66.98	—	—	—	0.35	10.92	0.89	20.86

Source: Mohd. Nour/Jantan et al. (1983)
a. High flow rate, 0.3 m^3/minute/t.
b. Medium flow rate, 0.1 m^3/minute/t.
c. Low flow rate, 0.03 m^3/minute/t.
d. Control, grain turning.

Table 4. Cost comparison for silo aeration at three airflow rates.

Treatment	Capital cost (US$)	Operational cost (US$/t)	Quantity of paddy (t)	Storage duration (months)
HFR[a]	10 840	1.42	687.47	3
MFR[b]	4 520	1.18	700.81	4
LFR[c]	3 540	0.45	318.32	3
C[d]	—	1.01	264.73	4

Source: Reproduced from Annexure 3 in the unpublished paper entitled Bulk storage padi aeration: preliminary report by LPN-MARDI.
a. High flow rate, 0.3 m^3/minute/t.
b. Medium flow rate, 0.1 m^3/minute/t.
c. Low flow rate, 0.01 m^3/minute/t.
d. Control, grain turning.

Table 5. Record of grain temperatures at various depths in a silo following aeration at three airflow rates.

Level (below grain top surface)	Average grain temperature (°C)			
	HFR[a]	MFR[b]	LFR[c]	C[d]
1	36.6	34.4		
2	36.8	37.3		
3	33.6	33.0		
4	36.2	35.7	34.8	33.0
5	36.1	36.2	36.2	34.5
6	28.0	28.7	28.1	27.5
Purata	34.6	34.2	33.0	31.7
Ambient temperature	32.5	30.0	30.0	30.0
Relative humidity	59.5%	70.8%	70.8%	70.8%

Source: Reproduced from Annexure 4 in the unpublished paper entitled Bulk storage padi aeration: preliminary report by LPN-MARDI.
a. High flow rate, 0.3 m^3/minute/t.
b. Medium flow rate, 0.1 m^3/minute/t.
c. Low flow rate, 0.01 m^3/minute/t.
d. Control, grain turning.

for grain turning, despite its unfavourable result, exceeded that for aeration by from 34 to 100%.

The MFR system appears to be most appropriate, as aeration can begin as soon as there is sufficient grain to cover the air ducts. In the case of the HFR system, aeration can begin only when the silo is full. The vertical ducts must be fully covered with grain to avoid short-circuiting of airflow across the head space (Mohd. Nour 1985). Another advantage of MFR is that the aeration ducts are very much easier and cheaper to install and maintain as compared with those for HFR aeration, where special equipment for accessibility is required during installation and for subsequent maintenance.

Based on the above findings, MFR aeration was extended to several LPN complexes having the same silo storage system.

Possible Areas for Further Work

Bulk storage in concrete tower silos is superior to other forms of storage because of the ease of grain unloading. However, it is evident that there are still some technical problems to be solved.

The following areas are identified as possibilities for further research and development.

Uniform Air Distribution

The existing air ducts for the HFR and MFR systems should be re-examined and modified to ensure even distribution of air within the grain mass. Particularly for the HFR system, care should be taken to minimise short-circuiting of air between the two vertical ducts. A more convenient and cheaper means of access to the vertical ducts should be devised for facilitating maintenance work if this system is to be adopted.

Aeration Frequency and Duration

More research is needed on the optimisation of fan operating hours and frequency, taking into account the local weather conditions.

Grain Cooling

The tropical climate is less suitable for aeration of bulk grain as the periods of lower air relative humidity always correspond with higher air temperature during the day, whereas higher relative humidities occur during the night when ambient temperature is low. As a result, aeration during the day risks raising the grain temperature, which will be conducive to microorganisms and insects. On the other hand, ventilation at night risks dampening the grain. A solution is perhaps to find means to cool the grain by refrigerated air. The overall economics of grain cooling needs to be investigated.

Pest Control

As explained earlier, under tropical conditions aeration with ambient air is ineffective in controlling insect infestation. Hence, there is a need to incorporate some chemical means to arrest grain deterioration caused by insects.

In addition, suitable methods and equipment should be developed for regular cleaning and disinfestation of the internal silo wall each time the silo is emptied. This is necessary to reduce the occurrence of reinfestation of grains during storage.

Grain Turning

Although the total energy cost for grain turning has been claimed to exceed that for aeration, a fast, independent grain turning system may be desirable for effective pest infestation control. Such a need should be further investigated.

Reduction of the Effects of Solar Heating

Studies should also be conducted to evaluate the feasibility of having all exposed surfaces of silos painted white to minimise moisture migration due to uneven heating of silo walls.

Up-grade Cleaning Facility

Sound grains store better. Storability of grain can be improved by ensuring its thorough cleaning before storage. There is therefore a need to examine existing cleaning facilities at the rice mill complexes with a view to up-grading them.

Conclusion

This paper has attempted to review the findings of aeration trials carried out by a joint LPN-MARDI research team. Further development work needed to improve the feasibility of silo aeration in Malaysia is outlined.

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Storage and Drying Trials with Unmilled Rice in Indonesia

D.J.B. Calverley*

Abstract

A system for the storage/drying of unmilled rice was designed for new 3500 tonne capacity stores being built in Indonesia. The concept was to use the relatively low humidity during the latter period of the day to dry grain from 18% moisture content at intake to 15%, and later from 15% moisture content to 12% using supplementary heat. Three trials were carried out in which paddy was satisfactorily dried. In the first trial, the moisture content at intake was about 16%. Drying during limited periods of the day reduced the moisture content to about 11%. In later trials the moisture content at intake averaged 22% but at times was as high as 28%. The loading was greater than the evaporative capacity of the installation and drying was completed by continuous ventilation throughout 24 hours. The final moisture content was 14%. It was concluded that it would be possible to dry paddy using ambient air in the most adverse climatic conditions in Indonesia. There were some quality changes following extended drying times, particularly an increase in yellow grains, but it was considered that some of these changes were due to damage and deterioration which had taken place before drying commenced.

Development of the Project

Badan Urusan Logistik (BULOG) was established in 1969 to bring order and stability to rice distribution and marketing in Indonesia by acting as an intervention and marketing agency. At this time significant changes were taking place in Indonesia's farming practices. Production of rice was increasing steadily; more area was being brought into production, more land was being irrigated, and fertilisers, pesticides, and new varieties were increasing yields and making possible more frequent cropping. These developments, however, brought their problems. New varieties mature less evenly, shed more easily, and cannot be left to dry on the stalk. Intensive cropping with more than two crops means that one harvest takes place during the rainy season. In the less populated parts of Indonesia there were harvesting problems which resulted in considerable deterioration where the crops were left unthreshed in the fields. BULOG was required to support producer prices under these conditions, often being forced to purchase lower quality unmilled rice which proved difficult to store without further deterioration and spoilage.

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At this time BULOG was embarking on an ambitious store building program. The Advisor to the Consulting Engineers was Professor H. Pfost, late of Kansas State University. Pfost studied the historical daily weather data for Java and concluded there were periods of most days, even during the rainy season, when the ambient relative humidity fell sufficiently to dry grain to at least 15% moisture content. Pfost therefore persuaded BULOG to modify some 175 godowns under construction to permit storage of unmilled rice (paddy) in bulk and drying with high volumes of ambient air.

Also at about this time (1975) the (then) Tropical Products Institute (TPI) was initiating a collaborative project with BULOG on pest and quality control in BULOG's stores and agreed to incorporate a series of drying trials in a modified godown. TPI prepared specifications for machinery and measuring instruments which were funded by the U.K. The godown and all structural arrangements were provided by BULOG. There were substantial problems in the design and construction of godowns intended to store bulk paddy up to a height of 5.5 m. There were also serious difficulties in the commissioning and operation of the handling equipment which delayed the commencement of the trials until 1981.

The Drying System Concept

The trials were carried out at the Food Technology and Research Centre of BULOG at Tambun, about 30 km east of Jakarta. This is in one of the most productive rice growing areas in Java, growing two, sometimes three, crops of rice each year. The major harvest starts in February during the wet season when the drying need is greatest. BULOG expected to be able to purchase paddy at about 18% moisture content (m.c.) and Pfost's concept was that this should be dried quickly to 15% m.c. using unheated ambient air, followed by a period of drying to 12% m.c. during selected periods of the day or using supplementary heat. In the event it was not possible to obtain paddy consistently at 18% m.c. and, in the second and third of three trials, paddy at moisture contents as high as 28% had to be accepted.

The capacity of the experimental godown was nominally 3500 t. The system was designed so that the crop would be loaded in layers on the drying floor at such a rate that no paddy would remain above 15% m.c. for more than 10 days. The drying capacity was rated at 3% moisture extraction (18%–15% m.c.) per 100 t intake per day. Drier ambient conditions would be selected to dry to 12% m.c. over a period of 3 months, possibly with the use of supplementary heat.

The experimental godown is 48 m long × 29 m wide (Fig. 1). The installation conforms to a conventional on-floor drying system (Fig. 2). There is a conventional twin intake arrangement at one end, each fitted with simple two-screen cleaners. The godown is filled from a single high level chain and flight conveyor and the paddy distributed with a belt grain thrower. The air supply is from a double inlet fan powered by 180 hp diesel and distributed through a central duct and above ground lateral ducts, each fitted with an

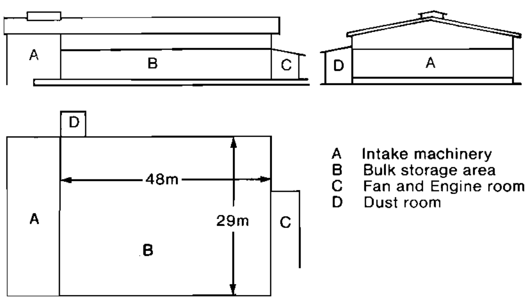


Fig. 1. Layout of bulk paddy godown used for storage/ drying trials at Tambun, Indonesia.

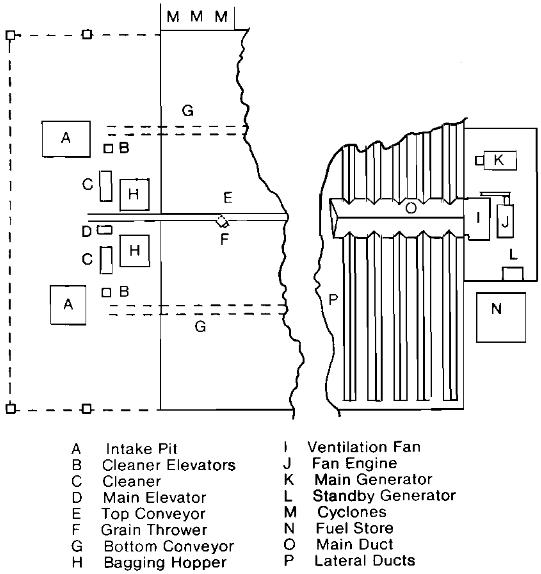


Fig. 2. Layout of godown equipment during storage/ drying trials with bulk paddy at Tambun, Indonesia.

air control door. The instrumentation to monitor the physical conditions of the grain was based on thermistors to indicate temperature and Reethorpe Moisture Monitors (Gough 1980) to indicate indirectly the moisture content of the grain. A comprehensive array of 600 sensors was designed for one side of the godown to measure moisture and temperature in small vertical increments in four vertical planes. A small array was designed for the other side as an aid to management to indicate the grain was being maintained in sound physical condition. It was a deliberate decision not to install automatic equipment at first, but to require each sensor to be read independently. The switching arrangements proved unsatisfactory and were later replaced by an automatic data logger, which also proved unreliable in the conditions within the godown.

Performance of the Mechanical Plant

Since the trials were intended to investigate the practicality of a drying technique, it was not considered that the suitability and performances of plant and equipment should be formally investigated. Accordingly, robust equipment of proven reliability with small grains was selected.

The machinery did not perform as well as expected. Many of the operational problems were the result of wear, which was considerably greater than expected in a number of places, and of the very high intake moisture content during the latter trials. Above about 22% m.c., the handling characteristics of paddy change markedly; it will not flow into or out of conveyors, or across cleaner screens. The problem is compounded when wet paddy is contaminated with straw, mud, and weeds, as commonly occurs with hand threshed, uncleaned paddy. This caused a particular problem with the cleaners. There was also considerable wear in the grain thrower. It was a well designed unit and problems associated with it are wholly attributable to the abrasive nature of paddy. However, the throwing action tended to separate out heavy and light particles giving an uneven distribution across the godown.

During drying, the paddy settled considerably and it then proved very difficult to initiate grain flow into the recovery conveyor. At times the grain face exhibited a negative slope. This consolidation required most of the grain to be shovelled to the discharge point, although once the grain was disturbed it flowed more or less normally. A portable auger reduced the distance that the grain had to be shovelled but the auger was quite unable to penetrate into the bulk of the undisturbed paddy.

There were breakdowns of the recovery conveyor chains fitted under the drying floor. These were of robust design and operated substantially below maximum design loading. The cause of breakdown was attributed to foreign objects falling into the conveyor, but the difficulties of repairing the conveyor during unloading operations make it important to consider alternative methods of unloading. There was also an inexplicable failure of the ventilating fan shaft during Trial II which caused delays in drying.

Drying Trials

Loading of paddy for the first trial started on 8 April 1981. Intake was slow at first, but later increased to a maximum of 500 t in one week. However, in 6 weeks up to 27 May, only 1730 t had been loaded in to fill the northern side and, because of procurement difficulties, intake was stopped. Since it was found very difficult to procure partially dried paddy, in the two subsequent trials it was decided that paddy direct from the field would be accepted at whatever moisture content it was offered. It was calculated that extending the period of ventilation up to 24 hours per day would ensure sufficient ventilation to achieve drying at the required rate *providing the rate of intake could be regulated.* In the event, the moisture content was higher than anticipated at a mean of 22% for Trials II and III and the rate of intake could not be easily controlled. Nevertheless, paddy straight from the field was dried to a safe moisture content. This decision proved to be a significant and, in the end, an advantageous departure from the original project concept.

The rate of change of the mean moisture content of the total grain in store is illustrated in Figure 3. The lower rate of moisture content reduction in Trial I is considered to be because the fan was run for much shorter periods each day and because the exhausting ventilation air did not reach saturation level, as it did in the later trials, because of the much lower initial moisture content at intake.

Moisture content profiles measured during the drying period exhibited the classical drying front moving upwards through the grain. This is clearly shown in Figure 4 for Trial III. The plots for June also show that very little paddy had dried below 14% m.c. as a consequence of extended daily ventilation. Only when the night ventilation had to be reduced in July because of objections to the noise of the engine did the lower layers become overdried.

Ventilation during selected periods of the day during Trial I resulted in the bottom layers being dried quickly to about 11% m.c. The fan was started as soon as the ambient relative humidity (RH) fell below 80% and was stopped when it rose above about 80%. The temperature increase in the ventilating air due to the waste heat of the fan engine was 2.5°C, which led to the average RH of the ventilating air being 65% in May and 60% in

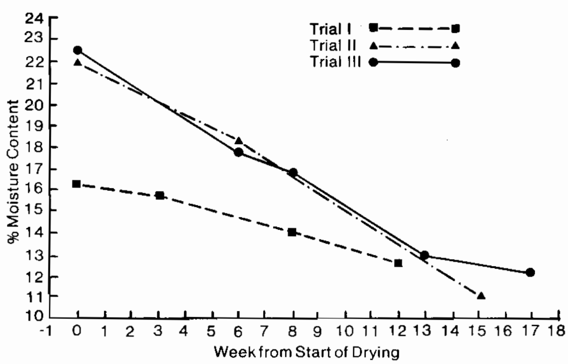


Fig. 3. Progress of drying of paddy during three storage/drying trials at Tambun, Indonesia.

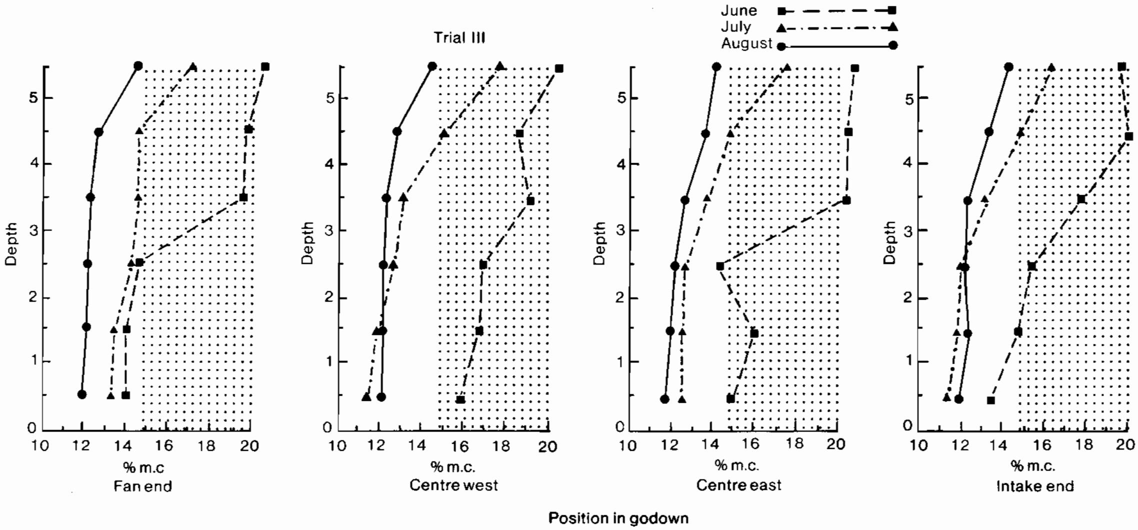


Fig. 4. Moisture profiles in bulk stored paddy during one of three storage/drying trials at Tambun, Indonesia.

June and July. This led to serious overdrying of the lower layers, ranging from 10.9% to 11.9% moisture content. In October 1981 (Trial I), the fan was run for 5 days continuously. The average RH of the ventilating air was 71.5%. As a result, the top layer dried from 14.1% to 12.6% m.c. and there was negligible change in the lower layers. This result was taken to show the feasibility of a management program to ventilate continuously. Later drying performances in Trials II and III confirmed that 24 hour continuous ventilation gave a higher daily rate of evaporation and less overdrying of the lower layers.

There were practical difficulties in persuading operators that it is not necessarily unwise or dangerous to leave reliable engines running unattended and there were also complaints from local residents about noise.

Assessment of Drying Performance

The original specification prescribed an airflow rate of 0.025 m^3/t/sec (50 cfm/t) at 127 mm (5 in.) water gauge fan static pressure. The pressure development was based on Schedd (1953). Whilst it was expected that compaction would have some effect on fan static pressure, the very large increase in airflow resistance, more than 50% above predicted levels, was not anticipated. Consequently there was a considerable reduction in the actual evaporative capacity of the plant. During Trial I the loading rate of wet paddy was less than the actual evaporative capacity of the plant (see Table 1).

During Trials II and III, paddy was loaded into the plant faster than it was dried. Accepting that the design provided for all paddy to be dried to less than 15% m.c. within 10 days of loading, it was considered that increasing this period from 10 to 14 days would constitute a 'permissible overload'. The actual loading rates and degree of overload are given in Table 2.

The permissible overload was exceeded by 26%

Table 1. Storage intake rates matched to actual evaporative capacity, during storage/drying trials at Tambun, Indonesia.

Intake moisture content (%)	Maximum daily intake (t)
18	68
20	41
22	29
24	23

Table 2. Loading rates of paddy into plant, during storage/drying trials at Tambun, Indonesia.

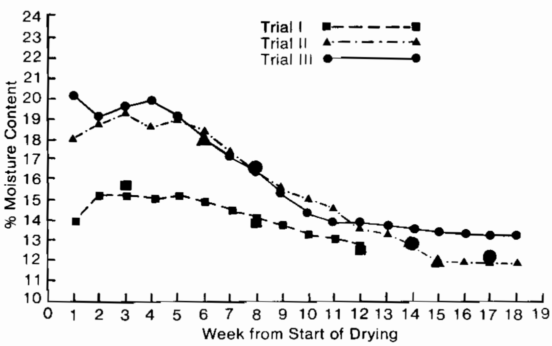
Trial no.	Intake rate (t/day)	Overload Permissible	Overload Actual	Excess over permissible
I	43	—	nil	—
II	50	19%	45%	26%
III	74	18%	60%	42%

in Trial II and there was no marked increase in deterioration. In Trial III, where the overload was 42% above permissible levels, there was some marked deterioration of the upper layers due to protracted drying.

The energy consumption at 3500 kJ per kg of water evaporated was high in relation to the range 1000–2000 kJ/kg experienced in temperate climates. Apart from the greater effective drying capacity of a temperate climate, the high power requirement at Tambun was compounded by the depth of grain and its consolidation, causing the fan to operate over less efficient sectors of its performance curves. Without considering building costs, using a centrifugal fan/engine combination as at Tambun, the best overall drying rates are achieved with about 2 m depth of grain.

A computer analysis was made of the ventilation data obtained during the trials, in particular to calculate the quantities of moisture removed from grain, in relation to the quantities of ventilating air and the degree of saturation of the air after passing through the grain. A good correlation was obtained between the theoretical and actual amounts of moisture evaporated. A simple mathematical model was used to simulate the process of drying using trial data (Fig. 5). Close correlation was obtained between calculated and actual performance. It is therefore confidently expected that the model can be used to predict drying performance for similar plants under different climatic conditions and for trials at different depths of grain and rates of airflow.

A later study incorporating this model and including an examination of the climate in



N.B. Actual M.C. represented by bold symbols.

Fig. 5. Changes in actual and calculated moisture content during three storage/drying trials with bulk paddy at Tambun, Indonesia.

locations below 200 m in altitude, in particular the mean hourly ambient relative humidity during times of the year that drying is needed, led to the conclusion that it is possible to dry paddy using ambient air with minimal supplementary heat in the most adverse climatic conditions within Indonesia.

Quality Changes during Storage

An attempt was made to measure dry matter losses occurring in three locations in the upper layers during a protracted period of drying, as occurred in Trials II and III. Losses ranged from 0.4–0.04% with a mean of 0.36%.

The amount of yellow and discoloured grain in the crop is considered an important indication of quality. BULOG's permissible maximum at procurement is 3%. During all three trials, the percentage of yellow and discoloured grains increased during the storage period (Table 3).

Table 3. Incidence of yellow and discoloured grains during storage/drying trials at Tambun, Indonesia.

Depth of layer from surface (m)	Average rate of deterioration (%/month)		
	Trial I 1981	Trial II 1982	Trial III 1983
0	0.62	0.50	1.53
1	0.56	0.49	1.30
2	0.54	0.21	0.91
3	0.52	0.30	0.96
4	0.48	0.39	0.70
5	0.38	0.39	0.92
Average	0.52	0.38	1.05
Standard deviation	0.08	0.11	0.30

In Trial I paddy was loaded into the store with 5.4% yellow grains. Within 4 months the quantity had increased to 9.1% in spite of the paddy being at about 12% m.c. Since it was not of particularly good quality and of unknown history, it was considered that increasing yellowing was a manifestation of damage or spoilage suffered before drying. An effort was made in Trial II to obtain better quality paddy. At intake, yellow and discoloured grains were 2.7%. After 6 months storage it was 5% and after 12 months it had increased further, but only to 12%. This was taken to indicate that once grain had manifested the predrying damage during the first period storage very little further deterioration takes place when the paddy is stored dry and under good conditions.

A linear regression analysis on the deterioration of discrete layers with respect to time showed generally that the layers which remained undried for the longer time deteriorated at a faster rate. In Trial I the surface layer deteriorated about 50% faster than layer 5. In Trial II there was no statistical difference between any of the layers. In Trial III, the top layer, being the longest undried, deteriorated at twice the rate of the bottom layer. However, it would be misleading to assume that all deterioration was the result of delayed drying. Paddy was dried almost immediately in the lower layers but it continued to deteriorate steadily in all three trials, reflecting the fact that the grain had suffered some damage and deterioration before being dried.

A linear regression analysis of monthly milling recovery tests did not give a clear picture. Trials I and III showed a reduction in recovery rate with time, but the correlation was poor. Low levels of recovery in Trial III were thought to be due to faulty laboratory techniques.

Conclusions

All three trials demonstrated convincingly that drying grain using ambient air in the humid tropics is both possible and practical. As the mean daily RH fell during the dry season the greatest concern was overdrying. It would seem, therefore, that the original design studies underestimated the drying potential of the climate at Tambun.

Increasing intake moisture content effectively increased the evaporative capacity of the plant. The greatest evaporative capacity is achieved by continuous ventilation. It may, however, be necessary to introduce a second phase of selective ventilation to achieve the final moisture content.

Grain at higher moisture contents spoils quickly. Therefore, as intake moisture contents increase, the quantities to be added daily should be reduced. However, if the amount of wet grain loaded onto the floor in excess of drying capacity is small, the risk of deterioration is small. If the loading in excess of drying capacity is continued over a long period, deterioration will become a serious problem. It therefore has to be asked, 'what risks of deterioration are acceptable to management in the interest of least-cost operations?'

It is therefore not possible to define engineering specifications for drying installations solely on the basis of these drying trials. Where drying requirements are precisely known, least-cost designs can be prepared, but they will be less flexible in operation than designs which necessarily incorporate a capacity for contingencies, but which will cost more.

Postscript

In relation to the present market intervention operations by BULOG, it must be concluded that BULOG's stores are too far removed from the point of harvesting, both in time and distance, to be involved in primary drying. It therefore seems evident it is in BULOG's best interests to maintain its present policy of not becoming involved directly in the procurement of wet paddy but to continue to promote and assist in every way possible the drying of paddy at cooperative and village level. However, it should be understood that whilst this project was carried out in relation to BULOG's operations in rice marketing, the conclusions and recommendations that developed from it can be applied to the drying of other durable commodities in the humid tropics without any substantial adjustment.

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Drying Technologies for Maintaining Grain Quality in the Philippines

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Abstract

The Philippines, being a humid tropical country, is beset with the serious problem of maintaining grain quality, particularly during the wet season when grains cannot be sun dried immediately. This is brought about by the prevailing high temperature and humidity and the high moisture content (26–28%) of the harvested grains, all of which favour rapid deterioration in quality.

Mechanical dryers are seen as essential now that the government is increasing its drive for food production and self-sufficiency. Despite the perceived need for dryers, however, adoption has been very low due to some socio-economic factors and unfavourable market characteristics. These are briefly presented.

Existing drying practices in the Philippines, from traditional sun drying to mechanical drying, and their problems and costs, are discussed, as are studies on drying technologies conducted by research institutions in the Philippines.

By using in-store drying in conjunction with high-speed pre-drying, it is hoped to alleviate drying and storage problems. Initial results of a study, from laboratory experiments on rice properties to pilot-plant drying investigations, are outlined. Recommendations for improving drying strategies at farm level, in farmer associations, and at government and private processing complexes are also presented.

In humid tropical countries such as the Philippines, grain quality deterioration is a serious problem, particularly during the wet season when most of the grains are harvested. The problem arises from the high temperatures and humidities prevailing in the grain-producing areas where grains are harvested at very high moisture content (26–28%). These conditions are conducive to rapid deterioration in quality. In the provinces of Isabela and Iloilo, two of the leading rice producing areas in the Philippines, the months of September to November are peak months of harvest during the wet season. These months have an average monthly rainfall of about 250 mm and an average monthly relative humidity of 84% (Tables 1 and 2). These conditions result in grain being harvested at high moisture contents favouring the growth of microorganisms. Quality deterioration is manifested by grain discoloration, yellowing of paddy and milled rice, decrease in head rice and milling yield, increased number of chalky kernels, high percentage of dry matter loss and, in some cases, formation of aflatoxins. Aflatoxins are carcinogenic substances produced by fungi when exposed to high moisture and temperature.

According to Teter (personal communication) an estimated decrease in quality of rough rice from premium grade to sub-standard grade will occur in 10 days if the grain is held at a moisture content of about 20.8% (wet basis). At higher moisture contents, a more rapid loss in quality will occur.

Present on-farm handling practices exacerbate the situation. Farmers often leave their fresh harvest in either conical or rectangular field stacks for several days before threshing, which is frequently delayed due to lack of threshers or manpower. Likewise, drying is delayed while waiting for sunshine or for mechanical dryers to become available. When drying is not possible, freshly threshed paddy is stored temporarily in bags.

Studies by Mendoza and Quitco (1984) of the National Post Harvest Institute for Research and Extension (NAPHIRE) simulating the delays in threshing and drying at the farm level and the delay in drying at commercial storages revealed significant occurrence of yellow kernels when threshing and drying were delayed.

A delay in threshing and drying of 1–7 days

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Table 1. Paddy production, average monthly rainfall, relative humidity, temperature, and number of rainy days for Isabela, Philippines during the year 1984.

	Production (cavans[a])	Average monthly rainfall (mm)	Average monthly rel. humidity (%)	Average monthly temp. (°C)	Average no. of rainy days
January	760 879	20.4	80	24.5	6
February	968 094	18.8	76	25.5	4
March	1 422 117	37.4	71	27.7	5
April	2 576 610	54.3	68	29.5	5
May	119 151	103.6	69	30.5	10
June	51 111	192.8	75	29.9	13
July	36 693	211.5	75	29.1	14
August	—	248.7	79	29.0	15
September	488 508	220.4	80	28.6	15
October	3 305 060	226.3	81	27.5	14
November	3 384 443	280.1	84	26.1	15
December	454 924	105.4	84	24.9	11

a. 1 cavan = 50 kg.

Table 2. Paddy production, average monthly rainfall, relative humidity, temperature, and number of rainy days for Iloilo, Philippines during the year 1984.

	Production (cavans[a])	Average monthly rainfall (mm)	Average monthly rel. humidity (%)	Average monthly temp. (°C)	Average no. of rainy days
January	1 005 720	42.0	83	25.7	8
February	2 759 526	20.0	81	25.9	6
March	1 217 450	33.7	77	26.8	6
April	228 327	38.6	74	28.1	5
May	96 496	137.7	77	28.5	12
June	75 472	258.7	82	27.9	18
July	65 472	280.1	84	27.4	19
August	799 140	332.8	84	27.2	20
September	2 412 126	242.6	84	27.2	19
October	2 054 528	212.9	84	27.3	17
November	729 796	184.0	84	26.9	15
December	528 154	95.0	84	26.2	12

a. 1 cavan = 50 kg.

resulted in 11.7–43.3% yellow kernels for a rectangular pile of 1.0 m × 1.0 m × 1.0 m and 19.7–71% yellow kernels for a solid conical field stack with a base diameter of 3.0 m and a height of 2.5 m. Threshed paddy not immediately dried displayed 1–22% yellow kernels within 1–7 days. These high percentages of yellow kernels could amount in monetary terms to losses of US$0.46–US$1.96 per cavan (50 kg) for a rectangular pile, US$0.82–US$4.39 per cavan for a solid conical field stack, and US$0.44–US$0.82 per cavan (US$ = PHP14.00) for threshed undried paddy (Table 3). In commercial storages, the 2% maximum yellowing for premium grade set by the National Food Authority (NFA) was reached after a one week delay in drying for paddy at 23–25% moisture content and after a one month delay in drying for paddy at 20–22% moisture content.

In addition, the frequency of heavy rainstorms during the wet season means that grains are often rewetted. As a result of rewetting, grains are subjected to moisture stress which eventually results in kernel fissuring and breakage, a sure indication of loss in quality.

With the increasing drive of the government to increase food production and preserve the quality and quantity of food produced, the problem of grain quality deterioration deserves serious and immediate attention. With the increasing volume

Table 3. Percentage of yellow kernels, with equivalent loss in monetary value, following holding of wet paddy by various methods.

No. of days of threshing/ drying delay	Piling method										Delay in drying	
	I[a]		II[b]		III[c]		IV[d]		V[e]			
	YK(%)[f]	PHPcav[g]	YK(%)	PHPcav	YK(%)	PHPcav	YK(%)	PHPcav	YK(%)	PHPcav	YK(%)	PHPcav
1	11.7	6.5	19.7	11.5	8.0	6.5	0.5	0	1.6	0	1.0	0
2	20.7	11.5	35.3	22.0	18.0	11.5	1.5	0	2.6	0	4.0	0
3	28.3	17.0	50.0	27.5	24.0	11.5	2.3	0	3.0	0	8.0	6.15
4	34.0	22.0	61.3	61.5	31.7	17.0	4.7	0	3.2	0	12.0	6.15
5	39.0	27.5	67.0	61.5	38.0	22.0	5.7	0	3.6	0	17.0	11.5
6	40.7	27.5	70.3	61.5	41.0	27.5	6.3	6.5	3.6	0	20.0	11.5
7	43.3	27.5	71.7	61.5	47.3	27.5	8.3	6.5	3.6	0	20.0	11.5

a. Retangular pile of 1.0 m × 1.0 m dimension.
b. Solid conical field stack with a base diameter of 3.0 m and a height of 2.5 m.
c. Hollow conical field stack with a base diameter of 3.0 m and a height of 2.5 m and an inside diameter of 0.75 m.
d. A cluster of unthreshed paddy consisting of 11 to 15 bundles built into a conical field stack after 3.0 days.
e. Bundled paddy hung on bamboo poles.
f. Yellow kernels.
g. One cavan (cav) is 50 kg.
US$1.00 = PHP14.00.

of grains harvested, the country can ill-afford the considerable penalties of allowing the grain to lose premium grade quality. The serious situation of wet grain handling therefore calls for an appropriate drying technology as the most effective method of preserving grain quality. At the same time, this drying technology must also meet the current emphasis on energy conservation, significant moves towards bulk rather than bag storage, and acceptability to end-users.

Present Drying Practices and Problems

Sun Drying

Sun drying is the most common method of drying high moisture paddy. In some areas, planting is timed so that paddy will mature after the rainy season to allow sun drying. Filipinos are inured to sun drying of grain and have the skills to use it to best advantage. Threshed paddy is spread on a flat, smooth surface, on concrete floors, straw mats, or hard soil, at 3 to 5 cm deep, and occasionally stirred (normally every hour) for uniform drying. Some paddy in unthreshed form is pre-dried in stacks in the field.

The temperature of the sun drying floor surface and the paddy may increase to as high as 60 to 70°C. This high, uncontrolled temperature induces severe temperature and moisture gradients within the paddy kernels resulting in a rapid drying rate and, consequently, stress checks and cracks. The resulting 'sun checking' of paddy is a common and too often, unfortunately, an accepted form of loss of rice quality. Sun drying is undoubtedly a low-cost method, but it is labour intensive and generally subjects the paddy to considerable quality deterioration.

Mechanical Drying

The paddy harvested during the wet season, especially in October and November, is still high in moisture content (26–28%) after threshing. Threshed paddy then needs to be immediately dried. During this period, sun drying cannot be relied upon, so the use of heated air, convection type dryers seems to be necessary. Almost every conceivable type of dryer adopted from the United States, Europe, Japan and locally is available in the Philippines. These dryers range from small (2 t capacity) fixed-bed dryers, to large, expensive and sophisticated continuous-flow dryers intended for centralised operations.

The mechanical drying systems vary according to:

- Fuel used for heating the drying air (oil, liquified petroleum gas, or rice hulls).
- The geometric configuration of the grain-holding device (flat bed or vertical column).
- The type of blower or fan forcing the heated air through the grain mass (centrifugal, axial flow, or propeller type).
- Drying air temperature and time of exposure

of the grain to the drying air stream. Batch dryers use 43°C drying air temperature to dry the grain continuously while continuous-flow dryers use 60°C drying air temperature for 15–30 minutes grain exposure time.

- Provisions for mechanical loading and unloading of the grain (bucket elevators, belt conveyors, oscillating rockers, or metering rollers).
- System of controlling and monitoring drying air temperature, grain moisture, and fire safety controls.
- Provisions for grain cleaning and dust control, and automatic weighing devices (sophistication required in industrial plant dryers).

The following types of dryers are in varying degrees of use in the Philippines:

- The University of the Philippines at Los Baños (UPLB) 2 t flat-bed dryer (rice-hull fed or kerosene fed).
- The International Rice Research Institute (IRRI) 2 t vertical-bin batch dryer (rice-hull fed or kerosene fed).
- The Louisiana State University (LSU) continuous-flow dryer with tempering bins and drying capacities of 1–5 t/hour (rice-hull fed or kerosene fed).
- The Danish Kongskilde vertical batch dryer, 2 t/hour (kerosene fed).
- The Danish Cimbria continuous flow dryer, 3 t/hour (kerosene fed).
- The Woodland continuous flow dryer, 2 t/hour (kerosene fed)
- The Japanese (Satake) batch-type recirculating dryer, 2.4 t/hour (kerosene fed).
- The Kuizon reversible airflow batch dryer, 1–6 t/batch (rice-hull fed).

Cost of Drying

Drying cost is usually computed as the ratio between the total operating cost of the dryer and its total capacity. It is used as one of the parameters in assessing the economic viability of a particular dryer and is usually expressed on a per tonne, per cavan, or per kilogram basis.

In computing the drying cost, factors to be considered are:

- drying capacity (expressed in t/hour)
- utilisation rate (hours or days/week)
- power and fuel used
- drying efficiency
- handling methods involved.

Studies made in the Philippines on costs of drying have varied in their assumptions, making it difficult to compare the costs of different drying systems.

Sun Drying

Villaroel and Cardiño (1984) reported that in Camarines Sur, farmers and private millers incur an average sun drying cost of US$2.40 per tonne and US$3.00 per tonne, respectively (US$1 = PHP10.00).

Batch Dryers

Mangaoang (1984) computed the drying cost of a rice-hull fed, flat-bed dryer to be US$5.80/t (US$1 = PHP7.50). This was less than the drying cost of a kerosene-fed dryer, which was estimated to be US$7.80/t. The computations were based on a 12 hour operating time, using a 6.8 hp gasoline engine.

In 1982, the National Food Authority (NFA) made a comparative study of the above dryers using actual costs. The results, which were based on a 600 hour/year drying operation, estimated the drying cost of a kerosene-fed dryer to be US$18.94/t (US$1.00 = PHP10.00). This was less than the drying cost of a rice-hull fed dryer (US$20.28/t). On the other hand, the Kongskilde, large capacity batch-type dryer (2 t/hour) had an estimated drying cost of US$21.16/t.

Continuous-Flow Dryer

In 1982, NFA also conducted a study on the drying costs of three makes of continuous-flow dryers: Cimbria, Satake, and Woodland. The results of the study were: Satake (2.4 t/hour), US$16.52/t; Woodland (3 t/hour), US$31.00/t; Cimbria (3 t/hour), US$52.70/t.

Among these three units, the Satake dryer was found to be the least expensive to operate, due to its capacity and high drying rates. The Cimbria dryer had the highest drying cost, because of its very high fixed cost.

Constraints to the Adoption of Mechanical Dryers

In spite of the recognition of the need for mechanical dryers to ease the drying problem, improvement of existing drying systems and the development of an energy-efficient and cost-effective drying system is still an urgent need. Tumambing (1984a) noted that the rate of adoption of, or investment in mechanical drying systems seems to have been very low, particularly in the private sector which handles about 50% of paddy production.

During the dry season, harvested paddy is commonly sun dried. During the wet season, only about 12% of the harvested paddy is dried by mechanical dryers. Of this, 10.8% is handled by the NFA and only 1.2% by the private millers and traders. At present, the total number and capacity of mechanical dryers available are not sufficient to dry the wet paddy, especially during the peak of the wet season harvest. On the other hand, mechanical dryers are underused during the dry and off-season harvests.

De Padua et al. (1984) summarised the constraints to mechanical drying as follows:

- Small-scale farming and low production volume at the farm level. Mechanical drying is rarely done by individual farmers simply because they do not have the harvest volume that would justify investment in, or use of mechanical dryers. Farmers claim that their low production volume does not permit them to make use of mechanical dryers.
- High fuel cost. While low production is a major constraint faced by small-scale farmers, mechanical drying has been practiced by farmers with large farms, by private millers, and by certain farmers' groups. However, many have stopped the practice due to their claim that rising fuel costs make mechanical drying no longer profitable.
- Lack of technical knowledge on drying. Farmers and millers who lacked understanding of the technical aspects of mechanical drying stopped the practice because, as they noted, mechanical drying gave them poor quality processed paddy. However, the poor quality may have been due to: (i) drying of paddy that was already spoiled; (ii) improper adjustment of temperature, airflow, and other drying components.
- Preference for sun drying over mechanical drying. It was observed that farmers and grain processors tend to make sun drying the basis of comparison in considering investments in mechanical dryers. Features of sun drying, such as simplicity and ease of operation, minimum operating expenses, and low capital costs, are the usual characteristics looked for by most farmers or millers intending to invest in dryers.
- Unavailability of dryers and ignorance of farmers of the existence of such equipment.

De Padua et al. (1984) also noted that, aside from the constraints in mechanical drying caused by factors in the micro-environment surrounding the farmer or grain trader/miller, other restraining factors present in the grain marketing system can be identified. These factors are enumerated as: (i) milled rice quality deficiencies, such as brokens, reduced head rice yields, and kernel discoloration, caused by the drying process but which are given little importance in pricing; (ii) existence of a market for low quality milled rice does not discourage millers from producing an inferior product; and (iii) inadequate price support by the government to cover the cost of drying.

Drying Studies in the Philippines

Warehouse-Type Dryer

Halos et al. (1983) describe the warehouse-type dryer using non-conventional sources of energy, developed by Dr Jeon of the International Rice Research Institute (IRRI). The heat source for drying is provided by a centre-tube furnace fuelled with agricultural wastes such as rice hulls, coconut husks, and sawdust. A vortex wind machine is to circulate the drying air inside the warehouse. The dryer (Fig. 1) has a capacity of up to 8 tonnes per batch, making it suitable for cooperative or village-level operation, or by a group of farmers or rice mill operators. It can be used for drying and storing different commodities in separate lots. Six tonnes of paddy can be dried from 20% to 14% moisture content in 6 hours using a drying air temperature of 39–42°C and air suction rate of 9.83 m³/minute per cubic metre of paddy. In terms

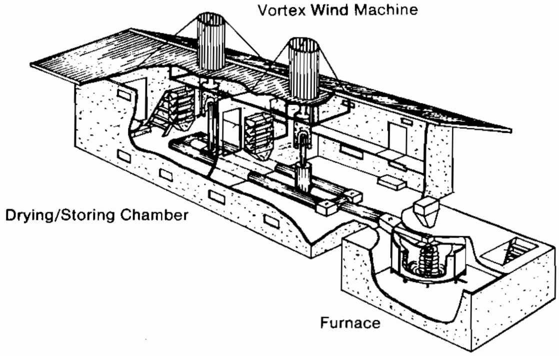

Fig. 1. Schematic view of warehouse-type dryer developed by IRRI (Halos et al. 1983).

of milling quality of dried paddy, milling recovery was found to be 67.5% and head rice yield 83.5%. A tonne of paddy dried from 25% to 14% moisture content entails a nominal cost of US$1.34–US$1.41 (US$1.00 = PHP10.00). This dryer will certainly be acceptable as an intermediate technology but application will differ widely due to variable weather conditions and agronomic practices between one area and another.

African Bush Dryer

Manilay (1984) describes a natural convection, African-type dryer developed by the Silliman University College of Agriculture (SUCA), suitable for drying maize. The dryer (Fig. 2) is made up of indigenous materials and uses firewood as fuel for the oil drum surface and heat exchanger. Air above the drum surface is heated and is induced upward by a removable plywood hood placed above a 2.4 m × 2.4 m × 0.25 m tray with perforated sheet metal flooring. At 25.3 cm depth of grain, the dryer is claimed to dry about a tonne of shelled corn from 23% to 14% moisture content in 5 hours.

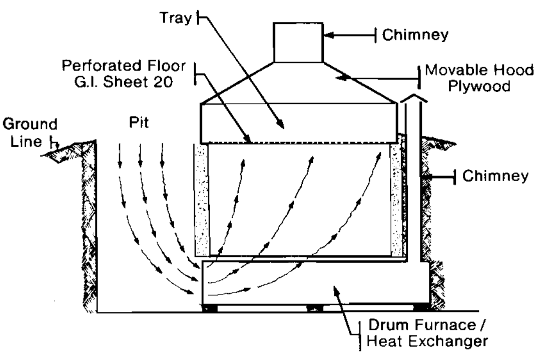

Fig. 2. Schematic drawing of the SUCA pit-type maize dryer.

IRRI Batch-Type Rotary Drum Dryers

Two batch-type rotary drum dryers, one heated directly, the other indirectly, applying the heat conduction principle, were designed by IRRI for drying higher moisture content grain down to 18% (Espanto et al. 1985). Both dryers (Figs 3 and 4) are manually operated and have a capacity of 25 kg per batch. Heat is provided by burning wood or rice-hull charcoal briquettes in a movable stove positioned beneath the drum. A batch of paddy, maize, or peanuts can be partially dried from 28% to 18% moisture content in 54 minutes, 33% to 13% in 80 minutes, and 63% to 42% in 110 minutes, with a grain temperature of 56°C. Thermal efficiency values were calculated to be 18.9% for the direct-heating dryer and 10.2% for the indirect-heating dryer. Potential milling recovery and head rice recovery values of the partially dried paddy were relatively high, but grain viability was relatively low. The dryers, which are still at the pilot stage, have potential but further study is required to ensure their adoption for farm-level pre-drying of grains.

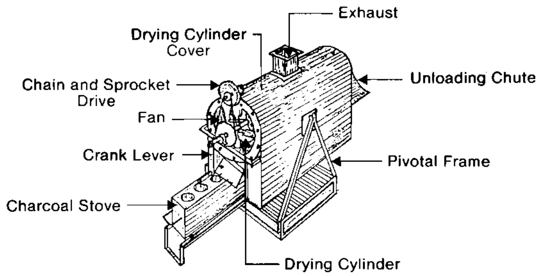

Fig. 3. Indirectly heated rotary drum grain dryer.

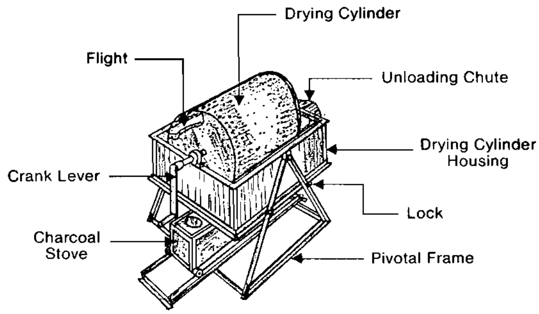

Fig. 4. Directly heated rotary drum grain dryer.

Pre-drying Handling of High Moisture Paddy Using Aeration

Rapusas et al. (1978) report a laboratory investigation on the application of aeration as a means of maintaining the quality of high moisture paddy held in temporary storage when drying is delayed. The experiment was conducted during the dry season using paddy with an initial moisture content of 24–27%. The results of the study revealed that, in the dry season, non-aerated paddy held in sacks maintained its premium grade quality for up to a 3-day delay in drying. Paddy held in sacks and aerated 8 hours a day with an airflow rate of 28 m^3/minute/t showed no decline in grade up to 9 days, while paddy in bulk aerated with an airflow rate of 35 m^3/minute/t lasted for 14 days without losing its initial grade quality. In the wet season, the non-aerated paddy held in sacks showed a loss in grade within a day of delay in drying. However, paddy held in aerated sacks and in aerated bulk at airflow rates of 28 m^3/minute/t and 35 m^3/minute/t respectively, maintained its quality up to 2 days in the former case and 3 days in the latter.

Field studies of the pre-drying handling of wet paddy conducted by de Castro et al. (1980) showed that delay in drying wet paddy greatly affected grain quality and milling recovery. Wet paddy with moisture contents of 23 to 26% maintained its milled rice quality within acceptable limits for about one week by aerating at an airflow rate of 6.0 to 35.0 m^3/minute/t for 8 hours a day. The milling recovery of aerated wet paddy decreased by about 1% for every 5 days delay before drying. Head rice yield was also found to decline, due to the increasing percentage of damaged and discoloured kernels.

In-Store Drying of High Moisture Grains in the Philippines

The Philippines, through its food marketing agency, the NFA, has been taking serious steps to shift from bag to bulk storage to accommodate increasing grain production, and at the same time eliminate the substantial cost of jute and plastic bags and reduce the risk of storage losses. About 17 bulk storage units integrated with drying facilities and materials handling equipment are installed throughout the country. The Agroprocessing and Marketing Directorate of NFA intends to instal additional units as part of its project to introduce commercially improved grain post harvest technologies in the Cagayan Valley region. These units vary from 250 t capacity, cylindrical Butler silos to 5000 t capacity, on-floor rectangular steel bins.

However, de Padua (1975) suggested that the successful operation of these silos is very limited, especially in long-term bulk storage. In most bulk storage units, heating, caking, fermentation, and insect infestation occur even when commodities are stored for only three to four months. These problems have been attributed mainly to mismanagement of the grain or the system itself and inherent engineering deficiencies in design or both. Many of the bulk storage systems have no provisions for turning the grain from one silo to another. The aeration systems of some silos perform poorly. Some silos have no aeration system. These variations in design and practice reflect a lack of relevant information, particularly on the physics of bulk storage as applied to humid tropical conditions.

The pressing and severe problems in drying and bulk storage call for a drying technology that will preserve the quality of the grain in an energy-efficient and cost-effective way. The drying technology should provide flexibility in meeting the different drying requirements at the level of both farmer association and government and private processing complex, for both dry and wet seasons.

Drying Strategy

Considering the high moisture content of the harvested paddy and the unfavourable weather conditions, especially during the wet season, Tumambing (1984) suggested that it is essential that the grain moisture content be brought down quickly to a level low enough to prevent grain deterioration. This consideration, coupled with the current emphasis on grain quality and energy conservation, suggest that grain drying has to be done in several stages, each one within an allowable storage time.

A two-stage or 'combination drying' system, in which a fast-drying stage is followed by unheated or minimally heated air drying in storage, offers potential for meeting the above needs. The fast-drying phase can be done by continuous-flow dryer, a batch dryer, or a flash dryer. The grain would be dried rapidly to a moisture content safe enough (18% wet basis) for final drying to be done in storage. In-store drying would then be accomplished by moving ambient or supplementally heated air slowly through the grain bulk to bring the moisture content down to the safe storage and milling level of 13.5–14% over a period or days or weeks. An in-store drying method which uses little or no heating fuel is currently being used in Australia. It is energy efficient and produces better grain quality as compared with conventional heated-air dryers.

NAPHIRE, on behalf of the Philippine Council for Agriculture and Resources Research and Development (PCARRD) is currently undertaking a research project based on the above drying strategy. The study is being carried out in collaboration with the University of New South Wales (UNSW) and Ricegrowers' Cooperative Mills Ltd (RCM) under the auspices of the

Australian Centre for International Agricultural Research (ACIAR). The project is a pioneering study on in-store drying of high moisture grains in the humid tropics. It seeks to solve the drying and storage problem by continuing the development of this technology and apply it to the drying of grain in bulk storage in the Philippines. Similar projects are under way in Malaysia and Thailand.

The two-stage or 'combination drying' system would provide flexibility in meeting the drying requirements imposed by different seasons and variable weather conditions. When the grain matures early during favourable field-drying weather, especially in the dry season, the fast phase of the drying operation could be partially eliminated and most of the grain dried in storage. On the other hand, the high-speed dryer could be run overtime to handle grain maturing late or during the wet season when there is inclement weather and heavy procurement.

Theoretical Considerations

Basic data have been gathered on the current situation in the postharvest industry in the Philippines, particularly as regards drying and storage, on drying requirements and energy resources for supplemental heating in drying, and on weather patterns and thermophysical properties of local rice varieties.

Weather records and data on rice properties were used as inputs to the computer simulation drying models developed at the University of New South Wales to investigate the feasibility of drying paddy in bulk storage in the Philippines. The results of the computer simulation suggest that, based on the climate conditions in Isabela, paddy could be dried using ambient air during the dry season. However, some form of supplemental heating would be necessary during the wet season. In practice, supplementary heating would be needed in both seasons to make the drying operation independent of weather conditions.

Physical Properties of Local Rice Varieties

The basic data on grain properties that are needed for simulating the drying process were determined for six local rice varieties (IR-42, IR-50, IR-52, IR-56, IR-58, and Sinang-Domeng).

Bulk density was measured for grains with 10–22% w.b. moisture content range. Together

Table 4. Equilibrium moisture contents[a] of six common Philippine rice varieties at different relative humidities and temperatures.

Relative humidity (%)	IR-42	IR-50	IR-52	IR-56	IR-58	Sinang-Domeng	F-value	Coefficient of variation (%)
				21.1°C				
52.9	10.32	10.78	10.20	10.02	10.61	10.84	1.94 ns	3.56
59.0	11.52	10.94	12.76	10.96	11.24	12.52	53.75**	0.93
75.4	13.76	13.00	13.59	12.98	13.15	14.06	21.28**	1.26
88.8	16.10	15.52	16.16	15.71	15.62	16.43	3.64*	2.05
92.9	19.05	18.32	19.26	19.08	18.72	20.62	9.88**	2.14
				26.7°C				
27.5	7.36	7.46	7.40	7.11	7.03	7.34	9.05**	1.32
58.0	11.38	10.75	12.09	—	—	11.56	9.04**	3.20
75.3	13.48	12.85	13.47	12.52	12.64	13.67	125.80**	0.58
86.6	16.06	15.12	15.59	14.85	14.93	15.86	406.55**	0.26
91.5	18.77	—	18.45	17.87	17.68	18.40	8.56**	1.45
				32.2°C				
25.0	6.72	7.11	6.74	6.32	6.55	6.74	1.86 ns	4.90
56.0	10.66	11.19	10.93	10.99	11.23	11.05	8.07**	1.12
75.2	13.26	12.31	13.14	12.18	12.34	12.84	2.00**	3.65
84.3	14.90	14.23	14.79	14.40	14.03	15.27	8.85**	1.85
90.1	17.29	16.56	17.22	16.81	16.97	17.85	15.58**	1.15

a. % wet-weight basis. Mean of three replications.
ns — not significant at 5% level of significance.
* — significant at 5% level of significance.
** — significant at 1% level of significance.
Missing data are not presented due to inconsistency of results.

with the grain density, the bulk density was used to calculate grain porosity. At lower moisture contents of 10–12%, bulk densities ranged from 539 kg/m³ (Sinang-Domeng) to 580 kg/m³ (IR-56), grain densities from 1083 kg/m³ (IR-56) to 1130 kg/m³ (Sinang-Domeng) and, hence, porosities from 0.465 (IR-56) to 0.523 (Sinang-Domeng).

Equilibrium moisture content (EMC) of the local rice varieties (equilibrated over supersaturated salt solutions) was measured at three temperatures (21.1°C, 26.7°C, 32.2°C) and five relative humidities (25, 60, 75, 85, 90% RH). The data (Table 4) revealed that at 75% RH, paddy moisture content ranged from 12.98 to 14.06% at 21°C, from 12.52 to 13.67% at 26.7°C, and from 12.18 to 13.26% at 32.2°C. These results indicate that, based on the recommended 14% final grain moisture content after drying, some rice varieties may be exposed to drying air with relative humidity slightly higher than 75%. This is particularly true in the case of ambient air drying.

Table 5. Summary of the results of low temperature in-store grain drying experiment conducted during January to February and April to June 1985 in the Philippines.

		January to Feb. 1985			April to June 1985					
		RUN 1[a]	RUN 2[a]	RUN 3[a]	RUN 1[a]	RUN 2[a]	RUN 3[a]	RUN 4[a]	RUN 5[a]	RUN 6[b]
VARIETY		IR-62	IR-42	IR-50	IR-56	IR-56	IR-60	IR-58	IR-90	IR-75
Initial moisture content		21.20	20.95	22.54	23.00	16.78	17.64	17.28	25.20	29.16
Final moisture content	% wet basis									
Average	% wet basis	13.90	11.97	12.95	11.95	13.19	11.09	10.70	10.69	13.05
Minimum	% wet basis	13.00	10.95	11.80	10.80	12.60	9.80	9.65	9.88	14.95
Maximum	% wet basis	14.80	13.60	14.40	14.95	14.45	13.60	13.10	13.74	14.95
Ambient air temperature										
Average	°C	26.1	26.2	27.4	29.4	28.1	28.1	31.5	30.7	26.6
Minimum	°C	21.8	21.9	19.4	25.5	24.4	25.3	27.8	26.7	23.6
Maximum	°C	30.2	31.7	33.3	33.9	32.2	34.4	35.0	34.9	31.7
Plenum air temperature										
Average	°C	28.6	29.4	32.8	36.11	33.9	33.9	37.22	35.0	31.6
Minimum	°C	25.0	25.0	27.2	32.2	30.0	32.8	32.2	30.7	28.5
Maximum	°C	32.1	36.9	38.0	38.9	37.8	39.4	42.2	39.4	36.9
Ambient relative humidity										
Average	%	72.0	77.3	71.8	70.1	79.8	68.2	67.9	66.0	84.8
Minimum	%	56.5	54.0	59.0	55.0	65.0	57.5	54.0	42.6	59.8
Maximum	%	86.5	96.0	93.0	97.0	91.0	81.0	84.0	86.0	97.0
Plenum relative humidity										
Average	%	62.5	63.9	52.9	53.1	58.0	49.4	50.6	51.8	62.9
Minimum	%	49.8	39.0	35.0	42.0	50.0	42.5	36	33.6	44
Maximum	%	73.5	80.0	71.0	62.0	68.0	55.0	62.5	69.0	70.4
Bed depth	m	2.15	2.30	2.10	2.20	2.20	2.15	2.15	2.20	2.00
Bulk density	kg/m³	599.3	566.6	606.6	592.1	578.7	607.1	592.2	578.8	605.0
Airflow rate	m³/minute/m³ paddy	9.0	5.4	6.0	3.6	3.6	3.7	1.9	3.6	4.0
Air velocity	m/minute	17.7	12.5	12.5	8.0	8.0	8.0	4.0	8.0	8.0
Plenum static pressure	Pa (in H_2O)	1868 (7.5)	897 (3.6)	897 (2.5)	623 (2.5)	623 (2.5)	623 (2.5)	311 (1.25)	623 (2.5)	623 (2.5)
Mass of wet grain	kg	1000	1000	1000	1023	934	970	961	1000	950
Mass of dried grain	kg	880	869	899	888	891	904	898	850	836
Water removed	kg	120	131	101	135	43	66	63	150	114
Drying period		Jan. 19–25	Jan. 27– Feb. 4	Feb. 9–15	April 11–17	April 22–28	May 8–12	May 16–22	June 7–17	June 23–29
Fan operating time	hours	65	107	87	110.17	79.83	59.33	86.59	109.78	158.00
Drying rate	kg H_2O/hour	1.85	1.22	1.15	1.22	0.54	1.10	0.73	1.37	0.72
Electric power requirement[c]	kW	0.91	0.30	0.30	0.14	0.14	0.14	0.04	0.14	0.14
Total electric energy consumption	kW/h	59.15	32.10	26.40	15.42	11.18	8.31	3.46	15.37	22.12
Specific energy requirement	kW/h/kg H_2O	0.49	0.24	0.25	0.11	0.26	0.13	0.05	0.10	0.19
Specific energy costs[d]	PHP/ton	118.30	64.20	52.8	30.15	23.94	17.13	7.20	30.74	46.57
	PHP/cavan	5.92	3.21	2.64	1.51	1.20	0.68	0.36	1.54	2.34

a. Intermittent drying operation (9:00 AM – 11:00 PM).
b. Continuous drying operation.
c. Efficiency of the fan n = 0.477.
d. Based on PHP2.00 per kW/h.

Sinang-Domeng, IR-42, and IR-52 varieties had relatively higher EMC values, probably because these varieties are more glutinous.

Pilot Bin Drying Studies

The pilot plant dryer found most suitable for effective and efficient drying of grains under humid tropical conditions such as occur in the Philippines is a two-stage 'combination drying' system (Tumambing 1985). The dryer comprises two drying bins. The first bin, for high-speed drying, has a base area of 0.78 m^2 and is filled with grain to a depth of 0.36 m. It is designed to dry 30% moisture content grain at 26°C and 72% RH to less than 18% m.c. in no more than 20 hours. The second bin is an in-store drying bin with a base area of 0.78 m^2 filled to a depth of 2.2 m (1 t) designed to dry grains with 18% moisture content at 28°C and 68% RH to 14% m.c. in 21 days. Each bin is equipped with a heater, centrifugal blower, humidity and temperature sensors, and computerised controller.

Table 6. Summary of the results of April to June 1985 high-speed grain drying experiment in the Philippines.

	RUN 2[a]	RUN 3[a]	RUN 4[b]
VARIETY	IR-56	IR-50	IR-58
Initial moisture content % wet basis	22.27	22.09	20.47
Final moisture content % wet basis			
Average	16.78	17.64	17.28
Minimum	15.60	16.80	16.70
Maximum	17.80	18.90	17.75
Ambient air temperature °C			
Average	31.2	30.4	32.8
Minimum	27.8	26.1	29.7
Maximum	33.9	33.3	35.0
Plenum air temperature °C			
Average	34.3	33.2	43.7
Minimum	28.9	27.2	35.5
Maximum	33.9	33.3	35.0
Ambient relative humidity %			
Average	68.0	74.1	66.1
Minimum	57.0	59.0	58.0
Maximum	90.0	88.0	77.5
Plenum relative humidity %			
Average	57.6	63.7	37.9
Minimum	49.0	52.0	28.0
Maximum	79.0	74.0	55.0
Bed depth m	0.36	0.36	0.36
Airflow rate m^3/minute/m^3 paddy	83.3	83.3	83.3
Air velocity m/minute	30.0	30.0	30.0
Plenum static pressure Pa (in H_2O)	623 (2.5)	623 (2.5)	623 (2.5)
Total weight of grain kg	1000	1025	1000
No. of batches	7	7	7
Weight per batch kg	142.9	146.4	142.9
Total weight of H_2O removed	56	55	39
Drying period	April 19–20	May 6–7	May 14–15
Total fan operating time hours	14.50	13.75	6.00
Fan hours per batch	2.10	1.96	0.68
Drying rate kg H_2O/hour	4.55	4.00	6.50
Electric power requirement[c] kW	0.51	0.51	5.51
Total electric energy consumption kW hour	7.40	7.01	33.0
Specific energy requirement kW hour/kg H_2O	0.11	0.13	0.85
Specific energy cost[d] PHP/cavan[e]	0.74	0.70	3.30

[a] Ambient air drying with supplemental heat from fan compression.
[b] With 5 kW electric heater.
[c] Efficiency of fan n = 0.477.
[d] Based on PHP2.00 per kW hour.
[e] 1 cavan = 50 kg.

A pilot plant drying experiment was conducted during the periods January to February and April to June (dry season) 1985 in Isabela, Philippines, to determine the proper combination of airflow rate and initial moisture content at a given grain depth and ambient air condition. Results of the experiment were very promising (Tables 5–7). The use of ambient air with supplemental heat from fan compression was successful as a drying strategy. One tonne of paddy 2.0–2.3 m deep was dried safely from an initial moisture content of 18–25% to about 14% in 60–158 hours, equivalent to a 5–12 day drying period. Optimum airflow rates were found to be 1.9 m^3/minute/m^3 paddy (4 m/minute equivalent air velocity) for paddy with 18% initial moisture content, and 3.6 m^3/minute/m^3 (8 m/minute equivalent air velocity) for paddy with 23–25% initial moisture content. Specific energy costs for optimum airflow rates were US$0.39–US$1.63 per tonne or US$0.02–US$0.08 per cavan (US$1.00 = PHP18.50).

Quality analysis of in-store dried paddy samples indicated no significant difference between them and naturally dried controls in terms of brown rice recovery, milled rice recovery, and germination rate, while quality was slightly improved in terms of crack ratio and head rice yield and recovery. Head rice yield was in the range of 45.7–59.4% of paddy weight, equivalent to a head rice recovery of 70.1–89.3% of milled rice weight. Lower head rice yield was a result of the high percentage of immature rice present. Crack ratio varied from 0.0025 to 0.22, depending upon the history of the grain. The highest value of yellow rice obtained was 1.95%, below the tolerable limit of 2.3% for premium grade rice. Dry matter loss varied from 0.05–0.87%, with the long varieties having higher

Table 7. Paddy condition after the January to February and April to June 1985 low temperature in-store grain drying tests in the Philippines, compared with a naturally dried control sample.

TEST MONTH	Expt. run	Variety	Brown rice recovery (%)		Milled rice recovery (%)		Head rice recovery (%) (head rice yield %)		Broken rice (%)		Immature rice (%)		Yellow[a] rice (%)		Crack ratio		DML (%)	Germination rate (%)	
	No.		C	ISD	C	ISD	C	ISD	C	ISD	C	ISD	C	ISD	C	ISD	ISD	C	ISD
January to February 1985	1	IR-62[b]	78.6	79.5	70.7	67.5	83.2 (58.8)	88.0 (59.4)	16.8	12.0	3.0	3.15	1.90	1.95	0.02	0.02	0.26	—	—
	2	IR-42[b]	74.8	75.6	62.2	64.9	89.0 (55.4)	89.3 (58.0)	11.0	10.7	11.3	13.7	0.50	0.45	0.099	0.094	0.27	—	—
	3	IR-50[c]	76.4	76.8	66.9	65.4	86.9 (58.1)	84.2 (55.1)	13.1	15.8	10.4	11.95	1.10	1.05	0.103	0.065	0.87	—	—
April to June 1985	1	IR-56[b]	76.9	77.3	67.2	66.8	78 (52.4)	79.7 (53.2)	22.0	20.3	17.9	19.1	2.40	1.00	0.082	0.162	0.26	95	97
	2	IR-56[b]	75.5	75.4	64.7	64.4	68.6 (44.4)	70.9 (45.7)	31.4	29.1	23.2	22.9	0.32	0.25	0.089	0.091	0.05	98	98
	3	IR-60[c]	76.9	76.8	65.7	68.6	76.2 (50.1)	77.2 (53.0)	23.8	22.8	31.5	31.7	0.38	0.32	0.237	0.221	0.10	91	95
	4	IR-58[c]	75.8	76.4	66.2	67.1	85.6 (56.7)	86.2 (57.8)	14.4	13.8	13.6	12.7	1.30	1.02	0.156	0.149	0.12	95	95
	5	IR-90[c]	72.8	73.4	63.5	64.2	79.4 (50.4)	85.5 (54.9)	20.6	14.5	14.2	16.06	2.14	2.80	0.016	0.015	0.63	—	—
	6	IR-75[c]	72.8	73.7	62.5	63.8	68.6 (42.9)	83.1 (53.0)	31.4	16.9	30.5	29.4	0.90	0.90	0.011	0.002	0.51	—	—

[a] No yellow rice was observed during April to June 1985 experiment.
[b] Medium grain.
[c] Long grain.
C — Naturally dried control sample.
ISD — In-store dried sample.

values. No visible mould growth was found in the dried samples.

The results of the experiment also showed that intermittent operation of the drying system is more energy efficient than continuous drying, provided that the drying time is within the allowable storage time of the grain. The energy needed to drive the fan and the energy costs are substantially less than for conventional heated-air dryers.

Conclusions and Recommendations

The need to dry high moisture paddy immediately after harvest, particularly during the wet season, necessitates the use of mechanical dryers to preserve grain quality. Many drying technologies are available but widespread adoption has yet to be realised due to some socio-economic factors and unfavourable market characteristics. In spite of the drying technologies available, it seems that there is a need for a dryer that would provide the flexibility to meet the different drying requirements for both wet and dry seasons. At the same time, the drying technology should be energy efficient, cost effective, and produce highest quality milled rice.

In-store drying, complemented by pre-drying using a high-speed dryer, has great potential to solve the drying and storage problem. In line with the government's move to shift from bag to bulk storage, however, successful operation of this drying strategy will be limited to commercial-scale drying, i.e. drying at private and government processing complexes, and will demand a well-designed structure and capable technical operators. Aside from that, a premium should be paid for high-quality milled rice.

The most recent detailed recommendations for improving grain drying in ASEAN countries were those presented at a 1984 workshop on wet grain handling sponsored by the ASEAN Crops Post-Harvest Programme (Frio and Manilay 1984). It is useful to restate them here:

1. The constraints to mechanical drying at the farm level are linked to the sociological and economic conditions prevailing in the marketing system. Activities should be geared more towards the improvement of traditional drying practices such as sun drying, natural air drying, drying using inexpensive fuel, and on-farm partial drying.
2. Farmers, by joining together in associations, could afford the use and/or purchase of mechanical dryers. However, the success of this approach depends upon the willingness of farmers to organise themselves in this way. The Irrigators' Association in Isabela, Philippines is considered as a promising group for the adoption of grain postharvest technology, particularly dryers.
3. Pre-drying and holding of wet grains, which pose the most serious problems, could be handled by both the government complexes (NFA) and the private millers. The latter could function as 'satellite drying centres', where the grain is partially dried to 18% moisture content to safely hold it before final drying and storage.
4. In the government complexes, pre-drying and holding of the grain could be done by the following systems:
   - use of bulk-aerated bins, in which may be pre-dried, as well as tempering/holding bins before the final drying process
   - aeration of plenum containing bag stacks
   - aeration of bulk paddy contained within walls of bagged paddy
   - flash drying using high airflows and temperatures with very short exposure and residence times of the grain mass
   - vortex wind pump machine as developed by IRRI, using biomass fuel or solar energy in combination with biomass.
5. Private millers should be encouraged to do more drying in their plants:
   - by making pre-drying technology available
   - by creating adequate incentives through pricing policy. Subsidies may be provided for purchases of drying units for partial drying. Cracked grain content should be penalised in the incentive pricing scheme to encourage investment in mechanical dryers
   - by making millers more aware of their social responsibility in preserving good quality grain for the country.
6. Research and development efforts should focus on:
   - development of appropriate partial drying technology both at goverment complexes and private mills
   - provision of mechanical drying incentive scheme for incorporation in the pricing and grading system
   - a socio-economic study of the marketing system of millers, traders and farmers, and their practices, relationships, etc. as information to influence grain marketing policies.

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Paddy Drying in Thailand

Somchart Soponronnarit*

Abstract

This paper describes the postharvest practices of Thai farmers. It also reviews previous work on on-farm grain dryers and drying with unheated air in Thailand.

A study was conducted on an integrated paddy drying and storage solar hut installed at a farmer's house in the central region of Thailand. It was found that the unit was technically and socio-economically feasible. It was suitable for drying 15 t of paddy per month and for storing 10 t.

Drying in bulk storage of high moisture paddy was studied under Bangkok's climatic conditions. It was technically feasible. However, two-stage drying was recommended, i.e., fast drying in the first stage until the moisture content is less than 20% (wet-basis), followed by drying in bulk storage with unheated air at a relatively low airflow rate.

RICE is the most important crop grown in Thailand. During 1983-84, 19.55 Mt of paddy were produced at an average yield of 2.04 t/ha (Anon. 1984).

The present cultivation techniques of Thai farmers are very labour intensive. The size of farms is relatively small. In the northeast, farm size is generally between 1.6–4.8 ha, while in the north it averages less than 3.2 ha. Farm sizes in the south and central regions are approximately 1.6–3.2 and 3.2–4.8 ha, respectively. There are few farms over 4.8 ha (Anon. 1976).

Rice may be grown once or twice a year depending upon the availability of water. The year crop is harvested in the dry season, while the second crop is harvested in the rainy season. The planting of a second crop has become more common, due to the expansion of irrigation systems. However, farmers have been faced with spoilage of the second crop when moisture cannot be reduced fast enough by field drying during the rainy season.

This paper reviews current postharvest practices in Thailand, particularly as regards the need for grain drying. Previous investigations on various types of grain dryers are outlined. The paper then gives the results of studies on an integrated drying and storage hut installed at a farmer's house and on laboratory studies of in-store drying and storage of paddy. The former concerns small-scale drying and storage of paddy, while the latter concentrates on the technical feasibility of in-store drying of bulk paddy in humid, tropical climates.

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Methods of Harvesting, Drying, Threshing and Storage

Most harvesting is done by hand, using a sickle, and it is often necessary to employ workers from other areas. For the year crop, the plants (with a grain moisture content of 20–22%, wet basis) are cut and left in the fields for a few days to reduce the grain moisture content by sun drying. The rice stems are then bundled and transferred to the threshing floor either by hand or using carts, tractors, or boats.

A different method is used for harvesting the second crop. Small bundles of cut plants are placed on the stubble with the panicles directed downward. Using this method, the grain will not hold water when there is rain. The bundles are transferred to the threshing floor when they have dried sufficiently. The harvest period is 2–14 days or more, most Thai farmers spending more than 14 days on harvesting.

Threshing the paddy by beating the cut plants on logs is quite common in the northeast of Thailand. Treading on the panicles, or driving cattle or farm tractors over the cut plants, is the usual threshing method in the central and the southern regions.

Engine-driven drum threshers are now relatively popular.

There are two methods used for cleaning the threshed paddy. In the north and northeast, winnowing baskets are usually employed. The other method of cleaning is by winnowing machine. These have been extensively used in many areas, especially in the central region. The machines may be hand or engine powered.

Paddy is stored for three main purposes: family consumption, sale, and seed for planting. Storage barns may be permanent buildings constructed from wood, with the floors elevated above the ground level to avoid flooding. Paddy is loaded and unloaded via doors. Semi-permanent barns are made from bamboo-matting walls covered with a mixture of soil and cattle dung. Each type is roofed to protect the contents from the sun and rain. There is no ventilation during storage. Some farmers do not store paddy either because they lack storage facilities or from a need to sell their crop immediately to obtain cash.

The storage period of paddy depends on its purpose. Those who grow rice for sale store paddy for a few months. For consumption and planting, paddy is stored for one year or perhaps longer. The main problems encountered during storage include invasion by birds, insects and rodents, yellowing of grain kernels, moulding, and poor germination because of rain. These causes of loss apply to both the year and second crop, but are more severe for the latter.

Some rice mills purchase wet paddy from the farmer, particularly during the rainy season. In this case, sun drying on a concrete apron is usually practiced. A few rice millers use high speed mechanical dryers.

Need of Grain Dryers and Comparison of Heat Sources

As noted in the previous section, cut plants are left in the field to sun dry. During the dry season, paddy is always safely dried in a few days by this method. However, it will not dry quickly enough during the rainy season. This leads to a loss in paddy quality, in terms of reduced head rice yield, yellowing, and moulding. This is a serious problem facing Thai farmers. To ameliorate it other methods of drying must be introduced. An attractive possibility is a mechanical dryer. This is composed of a bin as a drying chamber, a blower driven by an internal combustion engine or an electric motor, and a heat source such as electricity, gas, kerosene, diesel oil, agricultural waste, or solar energy.

An electrical heat source is quite simple, but operating costs are high. Gas and diesel oil are less expensive than electricity but control of heating is more complicated. Agricultural wastes, such as rice hulls, may be the most practical if they are available on site so that there are no transportation costs involved. Solar energy is freely available, but the solar collector is always expensive. If a collector cheap enough for farmers could be designed, solar-powered drying may be feasible.

Successful drying can be achieved by using either a high airflow rate and high drying temperatures, or a low airflow rate and near ambient drying temperatures. The latter may be called in-store drying and is interesting because of its low drying cost and the high milling quality of the product, particularly in the case of paddy.

Review of Previous Work on Grain Drying

Research and development studies concerned with on-farm grain drying have been conducted in Thailand for several years. Most of the dryers developed are of the batch type with drying capacities of 1–2 t and batch drying times of a few hours to a few days.

Srihavong (1978) studied hot air drying of paddy at 43, 49, and 60°C. The grain bed was 0.9 m deep and the airflow rates were 6.7, 13.3, 20, and 26.7 $m^3/min/m^3$ of grain. It was concluded that the drying temperature should not exceed 49°C to maintain high milling quality. To avoid high moisture gradients, the bed depth should not exceed 0.6 m.

A 2 t capacity farm grain dryer (fixed, flat-bed) was developed by the Ministry of Agriculture and Co-operatives, Thailand (Anon. 1977). Grain was dried by hot air at temperatures from 43–48°C. Heat was supplied by diesel oil or by burning rice hulls. When 1 t of paddy was dried with an airflow rate of 107 m^3/min, the drying rate was about 1.92% per hour. Fuel consumption was estimated to be 0.7 and 1.07 litres/tonne of paddy/1% (wet-basis) of moisture reduction, for a 6 kW diesel engine and a burner, respectively.

The International Rice Research Institute has developed farm grain dryers having fixed flat beds and fixed vertical beds (IRRI 1978). A 457 mm diameter tube, axial fan driven by a 1.5 kW electric motor or 2.3 kW internal combustion engine is used for a 1 t capacity fixed flat-bed dryer. For IRRI's 2 t capacity fixed vertical-bed dryer, a 533 mm diameter tube, axial fan driven by a 2.2 kW electric motor or a 3.7 kW internal combustion engine is employed. Air may be heated by burning kerosene or rice hulls. Their performance is similar to that of the dryers designed by Ministry of Agriculture and Co-operatives, Thailand (1977).

A low cost, solar rice dryer was developed by Exell and Kornsakoo (1977). The dryer is made of bamboo poles covered by a transparent plastic sheet. Air is naturally circulated above an absorber made of burnt rice hulls through the paddy layer, the optimum thickness of which is determined to be approximately 100 mm. It was able to dry about one tonne of paddy per sunny day and the same amount every three or four days during the rainy season.

All of the above dryers were implemented in rural areas but none was accepted by Thai farmers. For the case of the dryer designed by Exell and Kornsakoo (1977), Amyot and Sirisambhand (1982) pointed out that its non-acceptance was due to the following socio-economic factors.

1. Paddy is harvested as quickly as possible. As a result, the dryer can not keep up with the supply of wet grain. In order to use the dryer effectively, the farmer would have to stagger his harvest over a longer period. However, it is not possible to do this, because of unavailability of irrigation water during the planting season and the difficulty of finding agricultural workers at harvest time.
2. Rice traders and millers are usually uninterested in buying paddy in small batches.
3. The price received by the farmers for the paddy dried by solar dryer is not higher than that received for field-dried paddy.
4. The dryer is too flimsy. The plastic sheeting is constantly being torn by village dogs and children, or it simply disintegrates from exposure to the sun after a few months and has to be replaced.

Lhoste and Louis (1985) conducted a survey in Nakornpathom province. They found that some farmers stagger their planting and harvesting. It was also found that the price received for paddy depends on quality and moisture content. However, the most important problem would be lack of funds to invest in a dryer, because most farmers are in debt.

To make dryers more attractive to farmers, drying and storage should be integrated, so that paddy can be stored after drying and sold in large quantity when the price is reasonably high. The drying/storage unit needs to be durable even although this may increase its cost. In addition, it should be easy to construct and operate. Most importantly, some farmers already have storage huts, and if it were possible to modify these into drying/storage facilities this would result in minimal disturbance to existing practices.

Apart from the hot-air drying described above, drying paddy with ambient air has also been studied in Thailand. Uyeda (1984) designed and tested a simple on-farm paddy dryer. Natural air is forced through a 300 mm deep, gable-roof shaped paddy bed, by a 770 mm diameter axial flow fan driven by a gasoline engine with a continuous rated output of 2.8 kW at 1800 rpm. About 2 t of paddy can be dried each batch. From 7 runs of experiments during the wet season, it was concluded that paddy was successfully dried by natural air (final moisture content about 12–13%, wet basis). Estimated average drying rate (from 4 runs) is about 0.92% (wet-basis)/tonne of dry paddy/hour, and the average fuel consumption is 1.09 litres/tonne of dry paddy/1% (wet-basis) moisture reduction.

Drying paddy with ambient air was also studied at the Asian Institute of Technology, Bangkok by Jindal and Argarwalla (1979). Four runs of drying were conducted during the early dry season. Paddy was successfully dried with an airflow rate of 2.5–10 $m^3/min/m^3$ of grain at a depth of 0.6 m. The success was confirmed by a further 6 runs conducted by Pordesimo (1981) during the summer. The latter study used airflow rates between 4–7.5 $m^3/min/m^3$ of grain and a paddy depth of 0.6–0.9 m.

An Integrated Paddy Drying and Storage Solar Hut

An integrated drying/storage solar hut was designed with characteristics approaching the ideal dryer discussed in the previous section. It was constructed and tested at a farmer's house in Kampaengsaen, Nakornpathom, Thailand. The aim was to study its suitability from both technical and socio-economic points of view.

Design and Construction

The integrated paddy-drying/storage solar hut is

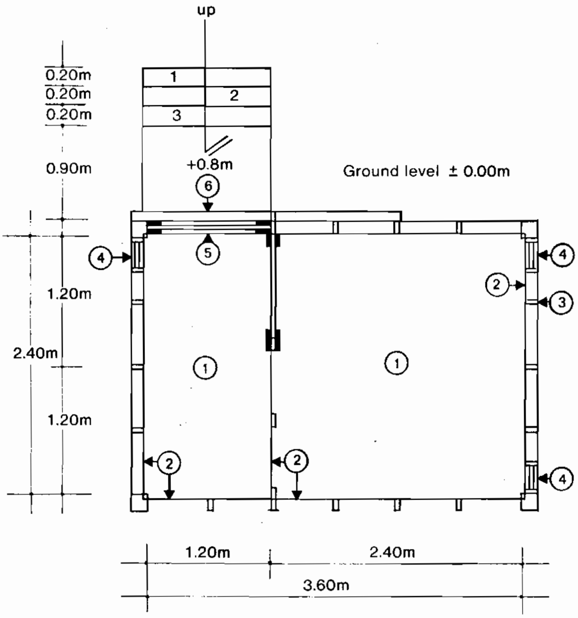

Fig. 1. Floor plan of integrated paddy drying and storage solar hut.

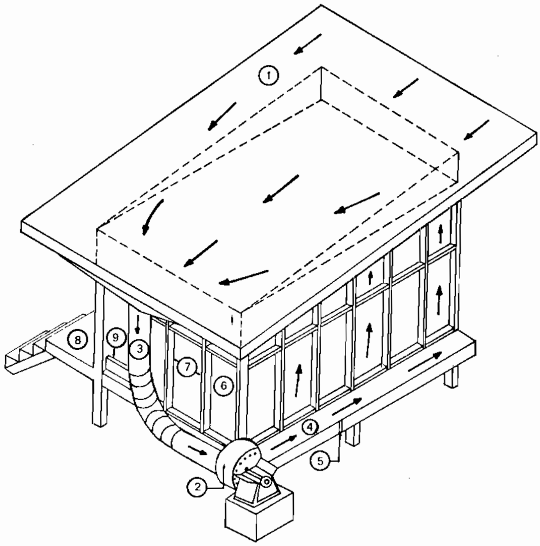

Fig. 2. Perspective drawing of integrated paddy drying and storage solar hut, showing direction of flow of heated air.

composed of a 18.6 m^2 flat plate, solar air heater, two drying/storage rooms, a fan, and an air duct system.

The solar air heater is similar to that designed by Soponronnarit (1984) and Soponronnarit and Tiansuwan (1984). It was built on the roof of the hut from corrugated, galvanised steel sheets (the absorber). In order to simplify construction, it has no transparent cover. Air flows through a 20 mm gap between the absorber and styrofoam 25 mm thick.

The space inside the hut is divided into two rooms having perforated floor areas of 2.9 and 5.8 m^2 (Fig. 1). About 1 t of paddy (0.6 m deep) will be dried in the smaller room and then transferred to the larger room for storage. However, both can be used for drying and/or storage. The maximum storage capacity is about 10 t at a depth of 2 m.

A 0.3 m diameter centrifugal fan, with forward-curved blades and driven by a 3.7 kW diesel engine is used to draw heated air from the solar air heater and pass it through the paddy bed in which drying takes place (see Fig. 2). The fan may be driven by tractor engine or electric motor. Normally, it will be operated during the daytime at 1500–1900 rpm, which corresponds to an engine speed of 1200–1500 rpm and a power requirement of 2.2–2.9 kW. Details of the method of calculation can be found in Soponronnarit et al. (1985b).

Measurements

Ambient air temperature, wet bulb temperature, inlet and outlet air temperature of the solar collector, and inlet and outlet air temperature of the blower were measured using mercury thermometers and recorded at hourly intervals. Air velocity profile in the duct was measured using a pitot tube. Global solar radiation was recorded using a bimetallic radiation recorder. Grain moisture content at the bottom, middle, and top layers (15–30 samples from three places in each layer) was measured by a 'Kett' moisture meter (ricetester model D) and then calibrated with the moisture content measured by the oven method (100°C for 72–96 hours).

Results and Discussion

Daily efficiency of the solar collector varied from 7–29% at an airflow rate of 0.027–0.041 kg/sec/m^2 of collector and with high variability in wind velocity. Heat obtained from the solar air heater varied from 20 to 81 MJ/day when global solar radiation was 15 MJ/m^2/day.

Three runs of drying experiments were conducted during the dry season and 10 during the wet season. Table 1 summarises details from 3 runs. It is estimated from the experiments that the drying rate is 0.64 and 0.3% (wet basis)/tonne of dry paddy/hour. Fuel consumption of the diesel engine driving the fan was 1.13 and 2.08 litres/tonne of dry paddy/1% (wet basis) moisture reduction, for drying paddy during the dry and wet seasons, respectively.

Head yield of paddy after milling varies from 45–50% and germination is greater than 92%.

About 7 t of dried paddy was stored in the solar hut for 5 months (January-May). It was found that the quality of the stored product remained high. There was no evidence of losses due to birds or rats.

The farmers who participated in this project were interested in drying wet paddy harvested during the wet season in order to prevent it from spoilage due to rain. They were also interested in storing paddy and selling it when the price is reasonably high. Their interest arose from the ease of operation of the hut and because it did not conflict with their traditional postharvest practices. However, they would not accept solar hut drying during the dry season because paddy can be dried easily in the field within 2 or 3 days. This is in spite of farmers knowing that losses in quantity and quality of paddy may be significant.

The solar hut is suitable for storing about 10 t of paddy and for drying 15 t of paddy per month. It costs 27 600 THB of which 21 700 THB is for materials (except engine) and the remainder is for labour (50 man-days) (during November 1985, 26 Thailand baht (THB) = US$1).

Farmers would benefit from the use of the drying/storage solar hut. For the year crop (harvested during the dry season), the benefit accrues from reduction of losses, better milling quality, and storage of paddy for selling at times of higher price. For the second crop (harvested during the wet season), it comes from reduction of losses, better milling yields, better quality (no yellow grains or moulds), and better prices for selling dry paddy. The net benefits are estimated to be 500 and 400 BHT/tonne for the year crop and second crop, respectively. The solar hut can dry and store 10 t of paddy per season. The net benefit per year is therefore 5000 + 4000 = 9000 BHT and the break-even point would be 27 600/9000 = 3 years.

More details of this study can be obtained from Soponronnarit et al. (1985b).

Laboratory Studies of In-store Drying

In-store grain drying is popular in temperate areas. The advantages of the method are that

Table 1. Results of wet season drying tests in Thailand using the integrated paddy drying and storage solar hut.

Experimental conditions	Test No. 1	2	3
Rice variety	RD 21	RD 7	RD 21
Mass of paddy after drying, kg	620	572	1172
Thickness of paddy bed, m	0.14	0.35	0.71
Average initial moisture content, % (wet basis)	27.5	17.7	17.8
Average final moisture content, % (wet basis)	16.2	14	15.1
Mean ambient temperature, °C	30.5	31.3	30
Mean ambient relative humidity, %	71	65	69
Mean inlet temperature, °C	33.4	34.2	32.7
Mean inlet relative humidity, %	62	55	59
Total temperature rise, °C	2.9	2.9	2.7
Temperature rise by solar energy, °C	1.8	1.4	1.3
Temperature rise by fan, °C	1.1	1.5	1.4
Flow rate, m^3/min/t of dry paddy	51.1	52.4	22.8
Total useful energy from solar collector, MJ	78	20.5	27.5
Total diesel oil consumption, L	13.7	4.48	7.5
Diesel oil consumption, L/t of dry paddy/1% (wet basis) moisture content reduction	1.69	2.1	2.46
Drying time, hours	20.8	7.4	12

drying costs are low and grain quality after drying is significantly improved. In tropical countries such as Thailand its utility is still questionable because of significant levels of microorganism activity and grain respiration stimulated by high ambient temperatures. The purpose of the study reported here was to determine, by way of laboratory experiments in a small test bin, the technical feasibility of in-store paddy drying under tropical climates.

Design of Drying Bin

Simulation studies of drying paddy in bulk storage using the Hukill (1947) drying model and the Seib et al. (1980) model of dry matter loss, show that, for Bangkok's climate, airflow rates of 1.8, 5.5, and 15.2 $m^3/min/m^3$ of grain are required to dry paddy from initial moisture contents of 20, 22, and 24% (wet-basis) to the final moisture content of 14% (wet-basis) so that dry matter loss is 0.5%. The corresponding drying times are 315, 126, and 54 hours, respectively. It is calculated that air has to be heated by 5–6°C for the worst month of 30 year weather data (Soponronnarit et al. 1985a). Paddy with a dry matter loss less than 0.5% will generally be classified as 1st grade.

A drying bin was designed according to the specifications of R.H. Driscoll and T.Adamczak of the University of New South Wales, Australia (Driscoll and Adamczak, personal communication). A 0.75 kW centrifugal fan and a 1.5 kW heater were selected by using the above simulation result. Air conditions could be controlled either by constant heating or by limiting the maximum relative humidity. The bin is made of galvanised sheet steel 1.5 mm thick, and has a diameter of 0.75 m and a height of 2.75 m. It is insulated with glass wool 25 mm thick and then covered by aluminum sheet. The maximum thickness of the paddy bed is 2 m. During operation, ambient air is sucked by the fan and delivered to the plenum chamber through a perforated steel sheet, and then distributed through the paddy bed.

Measurements

Moisture content of the grain was determined by the oven method. Grain samples of approximately 30 g were dried in an oven at 100°C for 72–96 hours. Grain and air temperatures, and dry and wet bulb temperatures of ambient air were measured by thermocouple (Chromel-Alumel, type K) and recorded by data logger ('Minitrend 205') at hourly intervals. The accuracy was about ±0.5°C. The profile of air velocity in the duct was measured by a hot wire anemometer. Visible mould, milling quality, yellow grains, and seed germination were determined after drying.

Results and Discussion

Eight runs of experiments on in-store paddy drying were conducted at King Mongkut's Institute of Technology, Thonburi, Bangkok during the wet season of 1984–1985. Harvested paddy was usually kept for about 2 days before drying, i.e., in rice panicles placed in the field for the first day and with threshed paddy in sacks for the following day. Each run involved approximately 420 kg of wet paddy (18–28%, wet-basis) at a bed thickness of 1.6 m (0.7 m^3). Airflow rates depended on the initial moisture content of paddy. They varied from 1.5–4.6 $m^3/min/m^3$ of grain. All paddy was successfully dried to 13% (wet-basis) moisture content in 71-180 hours. Head rice yield varied from 51–60% and germination was higher than 96%. No visible mould or yellow grain observed. The results are summarised in Table 2.

Drying with heated air was tested. Air was

Table 2. Results of laboratory tests of in-store paddy drying in Thailand.

Experimental conditions	Test No. 1/84	2/84	3/84	1/85	2/85	3/85	4/85	5/85
Rice variety	RD 21	RD 21	RD 21	RD 21	RD 21	RD 21	—	—
Mean ambient temperature, °C	31.3	31.5	31.2	30.6	30.4	30.8	30.7	32
Mean ambient relative humidity, %	81.8	82	82.2	79.7	83.2	82.4	81.2	81.4
Mean temperature of drying air, °C	34.9	34.7	35.4	36	42.1	33.8	33.3	33.5
Mean relative humidity of drying air, %	67	69	65	59	46.3	70.2	70.7	75.2
Mean airflow rate, $m^3/min/m^3$ of grain	2.88	4.61	2.26	4.55	1.46	3.3	2.89	1.49
Mean initial moisture content, %, wet basis	19.9	22	17.6	28.3	20.7	24.2	22.4	18.0
Mean final moisture content, %, wet basis	13	13	13	13	13	13	13	13
Drying time, hours	85	76	71	92	121	112	96	180

constantly warmed by a 0.5 kW electric heater for about 9–11 hours at night. Mean temperature rises were 5.4 and 11.7°C for runs 1/85 and 2/85, respectively. Paddy in the bottom layer was significantly overdried (9.6 and 7.3%, wet-basis), while the average moisture content of the whole bin was 13% (wet-basis).

Runs 1/84, 3/84, and 3/85 involved unheated air. However, mean temperature rises were relatively high, i.e., 3.0–4.2°C. This was due to the use of butterfly valves to reduce the airflow rate. As a result, the paddy at the bottom layer was overdried (9.9–10.3%, wet-basis). Runs 2/84, 4/85, and 5/85 also used unheated air but, rather than using the butterfly valves, surplus air was bypassed. It was observed that the higher the airflow rate through the paddy bed, the higher the mean temperature rise. However, mean temperature rises were lower than those obtained in runs 1/84, 3/84, and 3/85, i.e., 3.2, 2.6, and 1.6°C for the airflow rates of 4.6, 2.9 and 1.5 $m^3/min/m^3$ of grain, respectively. This led to a reduction in overdrying of grain, i.e., 10.5, 10.8, and 11.1% (wet-basis) at the bottom layer, corresponding to the above temperature rises, respectively. The comparison is relatively reasonable because the mean relative humidity of the ambient air was around 80–82% for all runs. It is therefore suggested that low airflow rates or apparent air velocities in the bin should be used, in order to avoid overdried grain as much as possible. Operating costs are also expected to be significantly reduced. Consequently, the maximum initial moisture content must be limited. If it is 20% (wet-basis), the minimum airflow rate required to dry paddy successfully is 1.5 $m^3/min/m^3$ of grain for Bangkok's average climatic condition (Soponronnarit et al. 1985a). This gives an apparent air velocity in the bin of 2.4 m/min for a bed depth of 1.6 m, as was used during the experiments. It should be noted that the bed depth becomes an important parameter when the economics of in-store drying are analysed.

Ambient conditions during the experiments were close to average for the wet season. They may be worse in some years. It is therefore recommended that a supplemental heat source of a few degrees of temperature rise should be provided.

Since initial moisture content is often higher than 20% (wet-basis), two-stage drying is recommended; i.e., fast drying to 18–20% moisture content (wet-basis) followed by in-store drying.

Conclusions and Recommendation

The integrated paddy drying and storage solar hut seems to be an ideal dryer for the farmer who harvests about 10 t of paddy per season and grows two crops per year. However, energy consumption for drying is still high. This is due to the use of a centrifugal fan which is needed to overcome the significant pressure loss in the system. It would be more economic if a tube axial fan which can provide high flow rate at low static pressure could be employed. In this case, unheated air should be used in order to reduce the pressure loss occurring in the solar air heater, air duct, etc. Consequently, overdried grain would not occur. It is therefore not necessary to transfer dried paddy from the drying room to the storage room because there is no need to separate them. The process then becomes in-store drying. If harvesting is staggered into 5–6 lots of 1.5–2 t each, spread over a month, it may be called layer drying i.e., the next coming layer will be loaded into the hut when the previous one is already dried. If 10 t of paddy having an initial moisture content of 20% (wet-basis) is expected to be successfully dried at a bed depth of 2 m, the minimum airflow rate and estimated power for a fan are approximately 0.4 m^3/sec and 200 W, respectively. If drying is completed in 381 hours, electrical energy consumption will be 76 kW-h or 7.6 kW-h/t of paddy.

On a larger scale, as in the grain industry, in-store drying is also favoured due to low operating costs and high quality results. It is suggested that two-stage drying is necessary, i.e., fast drying in the first stage until the moisture content is less than 20% (wet-basis), followed by in-store drying using a relatively low airflow rate. Supplemental heating may be necessary for the months which are unfavourable for drying.

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A System for Small-Scale Farm Drying and Storage of Paddy in Korea

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Abstract

For the purpose of loss reduction and quality retention of paddy rice at farm level in Korea, an in-bin drying and storage (IBDS) system (size: 1.8 × 2.4 × 3.2 m, capacity: 2–4 t of paddy), which consists of a fan and air ducts, was developed. Low-temperature, paddy drying with the IBDS system during the harvesting season was examined. The grain could be dried to a safe storage moisture content (14–15%) within 180–220 hours, by continuous aeration with ambient air. Even wet paddy (initial moisture content, 16–17%) could be safely stored for a year with proper fan operation. No significant changes in quality, in terms of milling yield, acid value, and germination were observed during the drying or storage. The IBDS system is considered one of the most economical and labour-saving systems for on-farm drying and storage of paddy in Korea. Information about it is being disseminated throughout the country.

RICE is the major staple food grain in Korea. Annual production is estimated at about 6 Mt. Per capita consumption during 1984 was about 135 kg. Paddy rice is harvested mainly in October. The conventional postharvest system of paddy rice in Korea is very laborious and considerable losses accompany it. The estimated quantitative loss of paddy rice is assessed in the range 8-10% depending upon the variety of rice, drying and storage conditions, and other environmental factors (Cheigh et al. 1980). In view of the labour shortage in rural areas in recent years, and the chronic food grain shortage of the nation, development of more efficient postharvest practices to reduce grain losses and the amount of labour required has therefore been an ever-present necessity.

In Korea, paddy harvesting begins from the end of September and continues for a month. Mature paddy with a moisture content of 22-24% is harvested mostly by hand, using sickles. In recent years, however, mechanical harvesters have been increasingly introduced to save labour. Traditionally, the cut plants are allowed to dry in the field to about 16-18% grain moisture content before threshing. The threshed grains are then further sun dried to a final moisture content of around 15%. Mechanically harvested paddy is often dried by fuel-fired commercial dryers. Although there are several methods of farm storage, most paddy for storage is bagged and stacked on the floor of storage house. In the course of drying and storage in such manner, paddy is exposed to birds, rodents, insects, and microorganisms, inviting considerable grain loss.

As Korea is located in the temperate zone, there are four distinct seasons. The average annual precipitation is approximately 1300 mm, most of it occurring between April and August. Only the frost-free period of seven months between April and October is suitable for cultivation. Most of harvesting activity takes place in the autumn between September and November, before the weather becomes too cold. As shown in Figure 1, from the end of September the monthly mean temperature stays below 15°C until the following April. The relative humidity remains at about 75%. These conditions suggest that the climate could be exploited in drying and storing of paddy in bulk, provided a proper system could be developed.

It would, of course, be possible to reduce such paddy losses if we were to introduce the mechanised systems which are quite popular in the industrialised nations. Regrettably, however, such systems are either technically or economically

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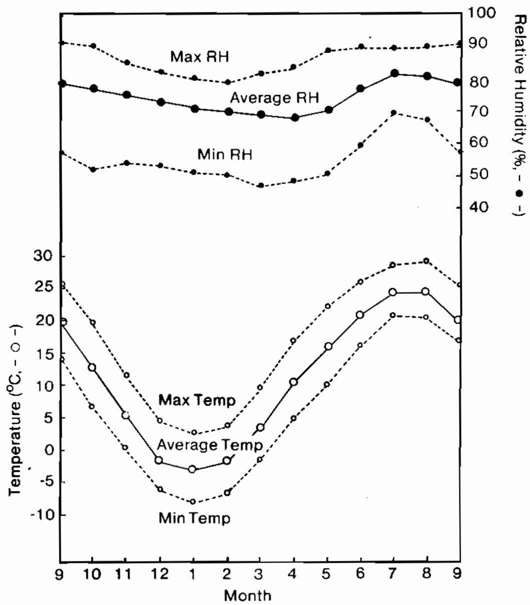

Fig. 1. Monthly average temperature and relative humidities at Suwon, Korea, 1971–1980.

unsuited to Korean rural conditions. We therefore focused our attention to how we might exploit our inherent climatic condition to meet postharvest requirements.

Under the joint sponsorship of the governments of Korea and West Germany, we undertook a research project on the development of drying and storage methods for paddy suited to small-scale farm use. This project was part of the research program on Integrated Rural Development Technology (Kwon 1983). From it we developed the KAIST (Korea Advanced Institute of Science and Technology) in-bin drying and storage (IBDS) system for paddy rice for the small farmer who harvests 2-4 t of paddy. Grouping by farm size showed that over 40% of all farm households lie within this range.

In this paper, we discuss the drying characteristics and storage capability of the IBDS system.

KAIST IBDS System for Paddy Rice

In developing and designing the KAIST IBDS system at farm level, the following attributes were considered desirable: capacity according to crop size; maximum natural ventilation; possible mechanical aeration; rodent proofing; prevention of water permeation from the floor as well as the walls; and low-cost facility with easy operation and low energy consumption.

Given these, it was decided to develop a natural air drying and storage system suitable for farm household operation. The idea of natural air drying, or in-bin low temperature drying, for grains is not new. It is in common use in Western countries, but only in large-capacity installations using facilities unsuited to small, individual farms (Cheigh 1982). Also, a recent study highlighted the possibility of using natural air for similar purpose in Korea (Cheigh et al. 1982, 1985). Another factor taken into account during development of the IBDS system was the threshing of paddy while the rice plants are still wet would substantially reduce the losses arising from longer handling and exposure to the possibility of rewetting by rain. In addition, in order to be accepted by rural infrastructure in Korea, the system should be of low cost and easy to construct and operate by farmers. Figure 2 presents the suggested direction for improving the present paddy drying and storage practices in Korea using the KAIST IBDS system.

Considering those factors, we have developed an in-bin drying and storage (IBDS) store (1.8 × 2.4 × 3.2 m) which is equipped with a fan (0.5hp) to blow air, and an air duct system (main duct and

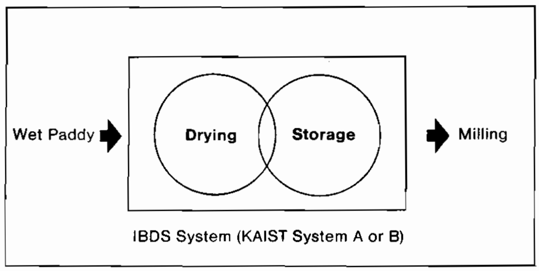

Fig. 2. Recommended paddy drying and storage system at farm level in Korea.

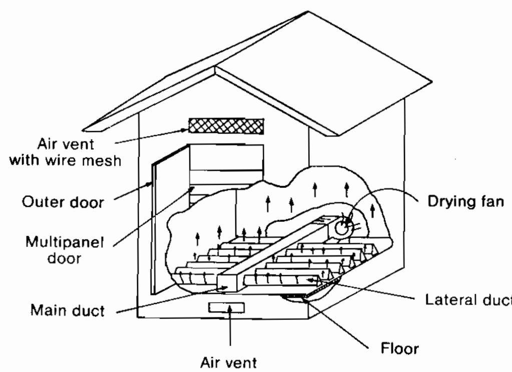

Fig. 3. Schematic drawing of the in-bin drying and storage (IBDS) system for paddy in Korea.

lateral) ensuring even air distribution through loaded grain bulk of 3-4 t, as shown in Figure 3. The store is constructed with cement blocks, insulation materials, wire-mesh, and waterproof paint, and therefore excludes rodents and moisture. Furthermore, the floor is above ground to prevent water and heat from that source. Finally, the loading and unloading portal has two doors, the inner one consisting of separate wooden panels to facilitate loading and unloading. Three tonnes of freshly harvested paddy can be loaded into the store for drying and year-round storage by blowing cool and dry air as needed.

In-Bin Drying of Paddy Using the IBDS System

A series of trials (1981-1983) with the KAIST IBDS system was carried out for the in-bin paddy drying, and the following results on drying capabilities for paddy in September-October 1982 are given as an example (KAIST 1983). Milyang #30, Indica type variety of paddy, was used for in-bin drying with KAIST IBDS system, which is located in Seoul. A total of 3.0 t of paddy was manually loaded into the system. The initial moisture content of the paddy was 21.4% and an aeration rate of 5.0 m^3 air/m^3 paddy /min was used.

Table 1. Results of paddy drying experiments using the in-bin drying and storage (IBDS) system.

Initial moisture content %, wet basis	21.6
Final moisture content %, wet basis	13.2
Drying period	27 Sept. - 9 Oct. 1982
Air temperature average, °C	18.6
Relative humidity average, %	63.3
Drying potential, kg H_2O/kg air	0.0018687
Airflow rate m^3 air/m^3 paddy/min	5.0
Grain depth, m	1.1
Mass of wet grain, kg	3 000
Mass of dried grain, kg	2 710
Water removed, kg	290
Drying time, hours	211

Experimental conditions and results are shown in Table 1, and a schematic diagram of the experimental IBDS system in Figure 4. Figure 5 shows the changes in moisture content of paddy at various depths during the drying period of 8.8 days (211 hours). At first, the drying rate of lower layers is much higher than that of upper layers. However, at the last stage of the drying, it was decreased rapidly. It took 4-5 days for lower layer, 6 days for middle layer, and 8 days for upper layer to be dried

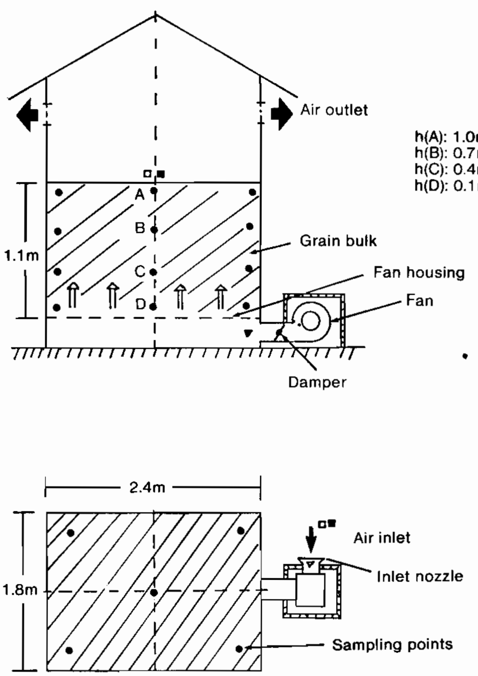

Fig. 4. Plan and elevation of an experimental in-bin drying and storage (IBDS) system for paddy in Korea.

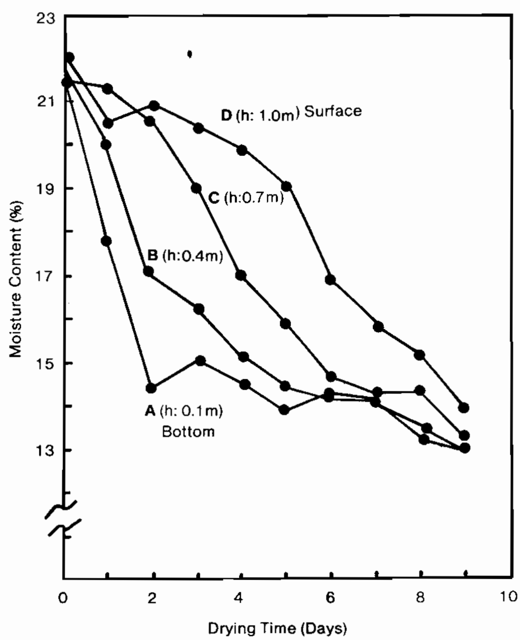

Fig. 5. Changes in the moisture content at various depths in paddy being dried using the in-bin drying and storage (IBDS) system.

to 14.7-15.2% moisture content, which is considered as safe level for storage.

The difference in moisture content before and after drying was about 8.4% and the mean drying rate was calculated as 0.040% per hour. The climatic data are presented in Figure 6. During the period of drying, diurnal temperatures fluctuated between 8.5 and 23.5°C and relative humidity from 24-94%. The average temperature was 18.6°C and the average relative humidity 63.3%. Generally, the air had a high drying potential (0.001869 kg H_2O/kg air) for in-bin drying of paddy and, as expected, this was reflected in the experimental results. Also, there were **no** significant changes in grain qualities such as milling yield, germination rate, amount of free fatty acids, and presence of microorganisms.

Storage of Paddy Rice Using the IBDS System

A comprehensive comparison between the storage capabilities of the KAIST IBDS System and traditional bulk storage was made throughout the year in 1979-1980. Paddy (Milyang #15 variety) was loaded manually to each store, two IBDS and one conventional. Paddy in the IBDS store designated Store 1 had a higher moisture content than that in Store 2. The amounts and initial moisture contents of paddy are shown in Table 2. At the beginning of the experiment, the paddy used had a somewhat higher moisture content than is considered safe for storage.

Table 2. Initial condition of paddy used in the 1979–1980 storage experiment comparing the in-bin drying and storage (IBDS) system, and the traditional storage method.

Store	Store condition	Paddy loaded (t)	Initial Moisture content (%)	Forced aeration
1	IBDS system (1)	2.1	18.1–19.2	When needed
2	IBDS system (2)	2.1	16.5–17.2	When needed
3	Traditional store	0.9	15.7–16.1	None

Temperature and moisture content of grain were measured once a week during storage. Changes of paddy qualities such as free fatty acid, hardness, milling yield, and germination rate were checked periodically.

The weekly grain temperatures at the centre of each type of store are shown in Figure 7. Grain temperature decreased until February and thereafter increased continuously to reach its initial level by the end of April. No significant differences of grain temperature were noted between the two IBDS stores.

The changes in moisture content observed at various grain depths during storage of paddy in IBDS Store 1 were as follows. The paddy showed some drying at the surface. Since there was a

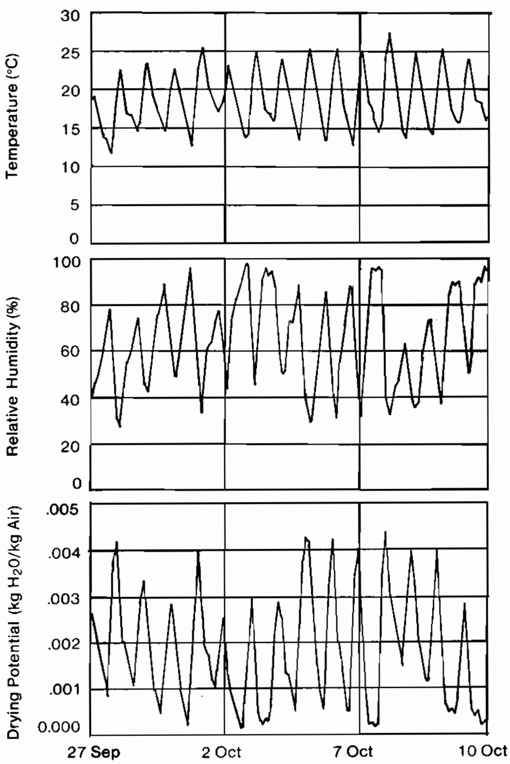

Fig. 6. Variation in drying parameters during an experimental paddy drying period in 1982.

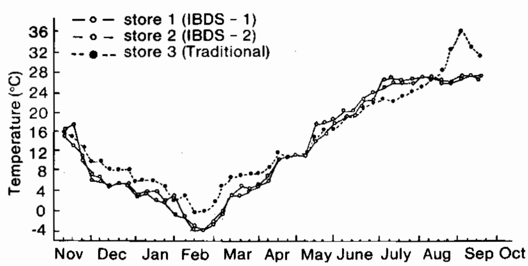

Fig. 7. Variation in grain temperature at the centres of three stores used in a paddy storage experiment in Korea.

tendency towards increasing moisture content from May, aeration was conducted. From this time the moisture contents of paddy stored in Store 2 (16-17% moisture content) was slightly decreased. However, the moisture content of paddy held in the traditional store increased by more than 1% at the bottom of the store, indicating absorption of moisture from the cement floor.

Some physico-chemical properties and milling data on paddy during storage were measured. There were no significant changes in free fatty acid levels, germination rate, or milling yield of paddy stored in the various stores during the term of the experiment. However, free fatty acid values rose after July, indicating that some chemical changes occur during summer.

It should be noted that even the paddy initially at higher moisture content (about 17-18%) can also be stored safely with proper aeration. However, some of the paddy rice in the bottom layer of the traditional store was contaminated by microorganisms and had deteriorated, even though its moisture content, at 15-16%, was not particularly high.

Dissemination of Developed IBDS System

To be economically viable and socially acceptable to farmers, new facilities or equipment must be simple, durable, trouble free and, if possible, locally made rather than imported. Also, the process must be simple and use little energy. In the conventional paddy-handling system in Korea the threshed grains are finally sun dried by spreading manually on a number of mats for 2–3 days under the sunshine. In the evening, the drying grain must be gathered up and held under shelter until the next sunny day. When it rains, the spread-collection operation has to be further repeated. The dried paddy rice is then bagged and stacked in a conventional flat store. The traditional system therefore requires a number of steps to be repeated. In addition, the flat store is usually exposed to factors causing considerable losses of grain. However, IBDS system is characterised by a low investment cost of about US$450 for each system, minimal requirement for labour, less attention and a lower energy consumption of 28 kWh/t (Kwon et al. 1985). It is also simple to operate.

However, although a new technology may be economically viable and socially acceptable, farmers in general are rather conservative and reluctant to accept new methods. Therefore, it may be desirable to involve farmers in the development of such technologies at an early stage of work, rather than imposing an unfamiliar system upon them. This approach not only gains the farmers' understanding, but also generates pride in participation. We made a special effort to work with farmers at village level, to use locally available materials and equipment of a durable nature, and to develop the simple processes for this technology.

We have made every possible effort to disseminate the IBDS system throughout the country, by the following activities:

- Technical training on the KAIST IBDS system for Government officers.
- Lectures to farmers and farm leaders on the construction and utilisation of the system.
- Publication and distribution of a booklet on the system.
- Construction and demonstration of the system in rural areas.
- Technical assistance to farmers wishing to install the system.

During 1982, about 30 IBDS systems were built and used by farmers in Kyongki Do Province from funds granted by Myon Branch-National Agricultural Cooperative Federation (NACF). In addition, 90 IBDS systems throughout the country (10 in each Province) were built with the support of the Office of Rural Development (ORD) as demonstration models. During 1982–1984, a considerable number of IBDS systems were built voluntarily by farmers.

As a result, we can now boast of a very successful dissemination of the IBDS technology throughout the nation. We, of course, gave the technology wide publicity through mass media, open lectures, travelling workshops, and answering farmers' letters and telephone calls on the subject. However, there was also strong support for the dissemination activities from Government agencies and other organisations concerned, and enthusiastic acceptance and cooperation from the farmers as well. As of 1984, there are already some 10 000 units of the IBDS systems installed. The number is expected to double by the end of 1985.

We were indeed very fortunate that we could use our own climatic conditions to develop effective postharvest systems for paddy in Korea.

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Grain Aeration in Australia

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Abstract

Grain aeration began in Australia in 1959 and is now applied to about 30% of all permanent storage. In the southern regions of the country, aeration of unsprayed, bulk-stored grain with ambient air has been used to obtain satisfactory insect control. In northern New South Wales and in Queensland, however, refrigeration of the aeration air has been found to be necessary because of the higher ambient temperatures. Nevertheless, aeration with ambient air has proven valuable in safely holding high moisture content grain sorghum in Queensland until drying can be carried out.

Case studies of 13 aeration systems are described, comprising 7 trials of natural aeration (5 in large stores and 2 in on-farm stores), 4 trials of refrigerated aeration in large stores, and 2 trials of aeration of high moisture content grain. Many of these trials involved experiments over more than one season.

Aeration has been shown to be beneficial for controlling grain insect populations, eliminating temperature gradients, reducing moisture migration, slowing down the degradation of pesticides, and preserving grain quality. Running costs of aeration systems are comparable with costs of insecticide treatment. The application of Australian aeration technology in the humid tropics is discussed.

Most Australian wheat and barley is harvested and placed into bulk storage during November and December, with grain temperatures ranging from 25°C to 40°C and moisture contents below 12% (wet basis). The storage period ranges generally from about 6 to 12 months. Wheat and barley used to be stored in Australia without treatment of any kind. This practice led to problems of insect activity which damages the grain and raises the temperature above the already high initial value, moisture migration which results in caking and mould growth at cold surfaces, and reduction in grain quality resulting from prolonged storage at high temperatures. The factors governing grain deterioration in bulk storage are described by Griffiths (1964), and experimental evidence of this phenomenon was obtained by Sutherland (1965, 1968).

Insects are the main cause of grain deterioration and dramatic reductions in their numbers were observed in the early 1960s when malathion, an organo-phosphorus pesticide was first introduced. However, it soon became apparent that stored products insects were becoming resistant to malathion and by 1973 resistance had been reported in 70 countries (Dyte 1974). Malathion is now virtually not used in Australia, but other chemicals have been introduced which are effective against grain insects (e.g. fenitrothion and bioresmethrin). However, these are also expected to have a finite useful life. Murray (1979) discussed the problem of insect resistance in Australia, which is contractually bound as a grain-exporting nation (approximately 70% of the annual wheat production of about 15 Mt is exported) to present its cereal grains onto the international market free from insects. In addition, customer concern about chemical residues remaining in food grains (termed 'pesticide shyness') is increasing. It is for these reasons that research has been carried out in Australia into non-chemical methods of grain insect control.

One such non-chemical method of insect control is grain aeration or ventilation, which is the process of cooling a grain bulk by passing through it air of suitable temperature and humidity. The basic principles of heat and mass transfer in air flow through fixed beds of grain have been described by Sutherland et al. (1971). They involve the formation of temperature and moisture fronts which move through the grain bed in the direction of the air flow. These fronts can interact which leads to an attenuation of grain temperature and moisture content profiles (Sutherland et al. 1983).

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Grain temperatures of 15–18°C prevent reproduction in insect pests such as *Rhyzopertha dominica* and *Tribolium* species and severely limit it in others such as *Sitophilus* species (Evans 1981). The dryness of Australian wheat also contributes to the lowered rates of reproduction of *Sitophilus*. Cooling to suppress insect activity is the main purpose of aeration, but there are other important benefits, such as the reduction of temperature gradients and consequently the suppression of moisture movement, removal of heat resulting from grain respiration, decreased chemical protectant breakdown rates, maintenance of grain freshness, expulsion of odours, and distribution or removal of fumigants.

Use of Grain Aeration

An aeration system comprises a fan and ductwork to distribute the air through the grain bulk, a controller to operate the fan only when aeration will be beneficial and, for conventional systems, temperature monitoring equipment to observe and optimise the cooling performance. In areas where ambient temperatures are too high to achieve adequate insect control, the air must be chilled before it is passed into the grain. In this case, it is also necessary to insulate the walls and roof of the grain store.

Grain aeration is widely used in Australia. About 30% of the permanent storage capacity have aeration facilities. The situation in the five main grain-growing States is shown in Table 1. The use of aeration at present ranges from 50% in New South Wales to 1% in Western Australia. Aeration has been applied to vertical silos (concrete and steel) and horizontal sheds of various shapes and sizes. The largest system known is at the Geelong terminal in Victoria, where two sheds with a combined capacity of 549 000 t and 43 silos with a combined capacity of 86 000 t, giving a total of 635 000 t, are under aeration. The system uses about 200 fans with a power input of over 1MW. The smallest commercial system which has operated in Australia was a 0.4 kW CSIRO farm aeration unit (Elder 1969) connected to a 100 t farm silo of maize near Newcastle in New South Wales (Wedd 1974). A description of experiments on grain aeration carried out by CSIRO is given in the next section.

Trials of Grain Aeration Systems

Natural Aeration

LARGE STORES

Melton, Victoria. The first trial of grain aeration in Australia was in 1959 at Wallaroo in South Australia, on barley stored in vertical steel silos. The first aeration in Victoria and the first CSIRO aeration trial was with wheat at Melton near Melbourne in 1963. The trial was conducted over three years and is described by Sutherland (1968). The store was a 2700 t capacity rectangular steel shed (25.3 m long by 15.8 m wide with wall height 7.6 m). The aeration system consisted of three half-round perforated ducts (7.3 m long and 1.2 m diameter) each connected to a non-overloading centrifugal fan, direct-coupled to a 3.7 kW motor. The design airflow rate was 1.5 L/sec/t. The airflow direction was upwards (a blowing system), and the fans were controlled by a high air wet-bulb temperature limit (Griffiths 1967) and a high air relative humidity limit.

Satisfactory insect control, at an acceptable cost and without the use of insecticides, was obtained. With no treatment, 11% moisture content wheat became badly insect infested, its temperature reached 38°C, and surface moisture migration and caking occurred. Aeration cooled the wheat of 10.5–12% moisture content to 9°C in eight months resulting in almost complete absence of

Table 1. Practice of grain aeration in Australia (August 1985). (Information supplied by the grain handling authority in each State.)

State	Permanent storage capacity (t)	Aerated storage (t)	Aerated storage % of capacity
Queensland	1 688 850	243 000	14
New South Wales	6 208 100	3 087 200	50
Victoria	2 500 000	1 104 180	44
South Australia	4 200 000	1 670 400	40
Western Australia	7 500 000	51 000	1
Total	22 096 950	6 155 780	28

insects. Moisture contents near the ducts increased to 14–16.5% leading to slight outloading difficulty in 1963 after 2300 hours of aeration, even though a high relative humidity limit of 75% was employed. In 1964 (1300 hours of aeration) and 1965 (1400 hours of aeration) no problems arose despite no relative humidity limit being used, showing that if care is taken to avoid excessive fan operation the relative humidity can generally be dispensed with. The capital cost of the aeration equipment, including three temperature detection cables but excluding a temperature measuring instrument, was nearly $AU6000, or $AU2.20 per tonne of store capacity (during November 1985, 1.5 Australian dollars ($AU) = US$1). The average energy used was 3 kWh/t and the average running cost was 9 cents/t (3 cents/kWh). This corresponds to 0.2 kWh/t per 100 hours of aeration or 0.6 cents/t per 100 hours. The setting of the wet-bulb temperature limit was lowered when continued aeration failed to produce any further reduction in the average grain temperature, showing that a temperature front had moved through the grain bed.

Beulah, Victoria. A further trial of aeration of unsprayed wheat was performed at Beulah in north-western Victoria in 1965 (Sutherland 1966a). The storage complex (Fig. 1), with a capacity of 9400 t of wheat, consisted of two identical units each made up of two large concrete bins (29.6 m high and 8.2 m diameter with a capacity of 1200 t), two small concrete bins (27.7 m high and 4.7 m diameter with a capacity of 300 t) and one steel annexe bin (13.1 m wall height and 14.5 m diameter, with a capacity of 1700 t). Each large bin had a 4.1 kW centrifugal fan connected to a half-round perforated duct (3.4 m long and 1.2 m diameter). One 2.2 kW centrifugal fan supplied two small bins, each having one half-round perforated duct (1.8 m long and 0.8 m diameter). Each steel annexe bin had a 3.7 kW centrifugal fan connected to a single submerged rectangular duct (7.9 m long by 1.2 m wide). The design airflow rate for each bin was 0.8 L/sec/t. The aeration fans were controlled by a high wet-bulb temperature limit and a high relative humidity limit on the ambient air.

The average wheat temperature in one large concrete bin decreased to 9°C after 1100 hours of aeration (downwards airflow — suction) in six months. In one steel annexe bin the average wheat temperature fell to 8°C after 1500 hours of aeration (upwards airflow — blowing) in eight months. In both silos, the average temperature was below 10°C by mid-July. No evidence of deterioration in grain quality was discovered, and no insects were obvious on inspecting the grain surface during the year. It was not until the last

Fig. 1. Storage complex at Beulah, Victoria (9400 t of wheat).

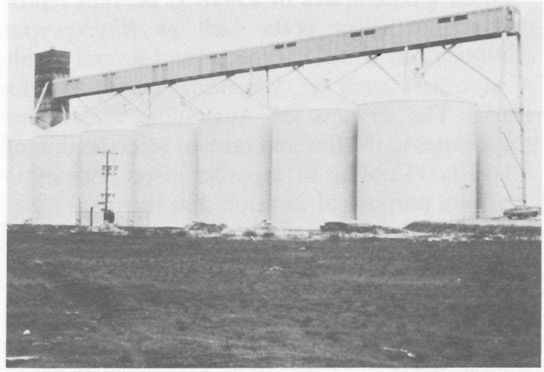

Fig. 2. Steel storage at Murtoa, Victoria (22 400 t of barley).

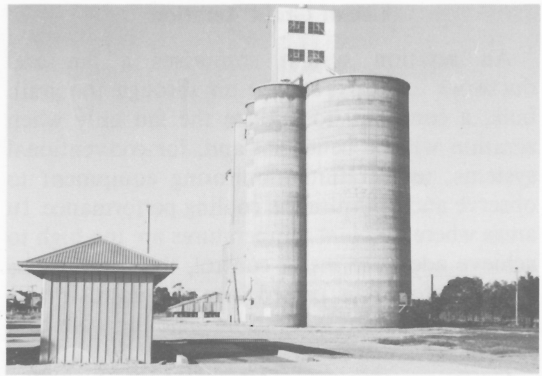

Fig. 3. Concrete storage at Rainbow, Victoria (3400 t of barley).

sampling that careful sieving uncovered a few live secondary insects, mainly at the peak of the bulk. No insects were found on outloading the silos even though no insecticide had been applied to the wheat. In a test on an unaerated bin, insect numbers increased, giving rise to a steep temperature gradient near the grain surface. The capital cost of the complete aeration system was $A16 000 ($A1.70 per tonne of store capacity), and the running cost was estimated to be 5 cents/t of wheat.

Murtoa, Victoria. The first trial of aeration combined with insecticide (malathion) treatment in Australia was carried out at Murtoa in north-western Victoria in 1965 (Sutherland 1966b). The storage (Fig. 2) holding 22 400 t of barley consisted of 14 steel silos (14.9 m wall height and 14.5 m diameter with a capacity of 1600 t of barley). Each bin had two half-round perforated ducts (4.6 m long and 0.8 m diameter) along the hopper bottom, connected to a non-overloading centrifugal fan, direct-coupled to a 3.7 kW motor. The design airflow rate was 1.0 L/sec/t of barley, and wet-bulb temperature and relative humidity control was employed.

Aeration in two bins (one with upwards airflow and the other downwards) reduced malting barley temperatures to 8°C after 1200 hours of aeration in eight months of storage. No insects were found, and cooling of the grain prolonged the life of the malathion, which has been found to degrade rapidly above 20°C and 12% moisture content (Minett et al. 1968). The capital cost of the complete aeration system was about $A24 000 ($A1.10 per tonne of store capacity). The running cost was 5 cents/t (0.4 cents/t per 100 hours of aeration) which was comparable with the cost of application of malathion spray at 12 parts per million.

In a further aeration trial at Murtoa in 1966 on two bins of unsprayed wheat, one was cooled from 30°C to 10°C after 1100 hours of aeration in eight months and the other was cooled from 27 to 10°C after 1000 hours of aeration in eight months (Elder and Sutherland 1970).

Rainbow, Victoria. Another trial of aeration combined with malathion treatment was carried out at Rainbow in north-western Victoria in 1967 (Sutherland and Elder 1969). For this 3400 t barley storage (Fig. 3) each of the two large concrete bins (25.9 m high, 10.7 m diameter and holding 1360 t) was fitted with a 4.1 kW two-stage axial fan, and each of the two small concrete bins (25.9 m high, 5.5 m diameter and holding 340 t) was fitted with a 2.2 kW centrifugal blower. Submerged aeration ducts (V-shaped in plan) were used being 7.8 m long and 0.8 m wide (each leg of V) in the large bins and 3.4 m long and 0.4 m wide in the small bins. The design airflow rate was 1.0 L/sec/t of barley. Aeration was in a downwards direction and controlled by a high wet-bulb temperature limit and a high relative humidity limit. The relative humidity control was achieved by measurement of the wet-bulb depression of the air and not by the use of hair elements as in the previous systems.

In one large bin, the average centreline temperature was reduced from 30 to 13°C after 1200 hours of aeration in seven months. In the other large bin, the average temperature fell from 26 to 13°C after 1070 hours in eight months. Average barley moisture contents remained unchanged, there was no drop in germination percentage, and no insects were found during inspection at the peak of the bulk, through the bulk, and on outloading.

Kingaroy, Queensland. A trial aeration of peanuts-in-shell was carried out at Kingaroy in southern Queensland over two seasons (1970-71 and 1971-72). Three concrete bins (26 m high, 6 m diameter, and holding 170 t of peanuts-in-shell) were each fitted with a 0.6 kW axial fan giving an airflow rate of 2.5 L/sec/t.

All the fans were connected to a CSIRO time-proportioning aeration controller (Elder 1972).

Aeration combined with malathion application kept the peanuts-in-shell in good condition for a storage period of 10 months (Ghaly 1978). Analysis of bulk samples showed the average infestation level of the aerated bins to be significantly less that that of the unaerated bins. Free fatty acid content was also less in the aerated bins. There were no significant differences in viability and appearance of the kernels between aerated and unaerated peanuts.

FARM STORES

Albury, New South Wales. Two steel farm silos holding 28 and 44 t of oats were aerated for a period of two years (1969 and 1970) using two outlets of a 0.4 kW CSIRO farm aeration unit (Fig. 4) at Albury in southern New South Wales (Elder 1969). The silos had a wall height of 4.5 m, with the larger one having a diameter of 4.9 m and the smaller one 4.0 m (Fig. 5). Two full-round aeration ducts (each 2.4 m long and 0.15 m diameter) were

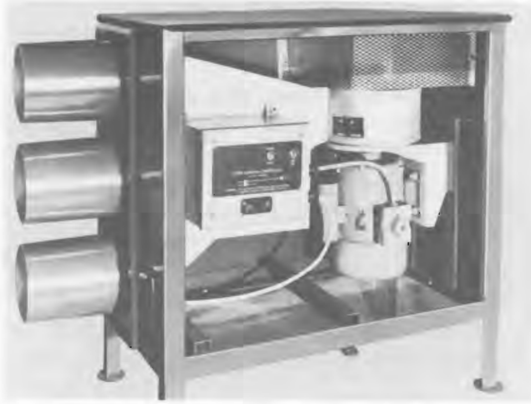

Fig. 4. CSIRO unit for farm aeration of grain.

Fig. 5. Steel farms silos at Albury, New South Wales (28 and 44 t of oats).

placed along the hopper bottom of the larger silo, and one duct (2.0 m long and 0.15 m diameter) supplied the smaller silo. The design airflow rate was 1.6 L/sec/t of oats.

The oats in both silos were kept in good condition even though no chemical treatment was applied (Elder 1971). The average centreline temperatures were kept between 8 and 18°C, apart apart from the first three months after harvest. Grain temperatures near the north wall remained high enough to permit some insect reproduction for much of the storage period. This was partly offset by some drying of the grain near the walls, as a result of repeated conduction heating and aeration cooling. The level of insect infestation was kept under control, although there was a large seasonal variation. Insects generally congregate at the peak of the grain bulk where they are accessible for chemical treatment if required. The moisture content of the oats reached 13% (wet basis) near the aeration ducts in both bins, and the average increased from 10 to 11%. Germination tests showed no deterioration in quality after two years storage.

Dookie, Victoria, Aeration of two steel farm silos, each having a capacity of 54 t of wheat, was performed at a flow rate of 2 L/sec/t using a CSIRO farm aeration unit and controller at Dookie in north-eastern Victoria. The flat-bottomed bins were 4.5 m diameter and had a wall height of 4.5 m. The full-round aeration ducts were 3.7 m long and 0.15 m in diameter.

In the first trial (1969-70), unsprayed wheat of 11% moisture content was stored successfully under aeration for 18 months, whereas an unaerated bin had to be fumigated. Wheat temperatures were reduced from 27 to 18°C in three months in the aerated bins (Williams and Elder 1979). The number of insects found in the control silo at outloading was 70 times the number (live plus dead) in one of the aerated silos. The other aerated silo was exposed to the heat of the sun and became infested at the north-western wall.

Greater cooling at the north-western wall of the exposed silo was achieved in a second trial (1971-72), by placing the aeration duct in the north-western sector of the bin floor (Ghaly 1984). This suppressed insect numbers to the same level as for the partly shaded silo. After four months of aeration, the average wheat temperatures at the centre of the silos ranged from 11 to 21°C for the next 14 months. The average wheat moisture contents increased by 2% as a result of aeration.

Refrigerated Aeration in Large Stores

Dalby, Queensland. The first refrigerated aeration system for grain in Australia was installed at Dalby, southern Queensland in 1967 (Sutherland et al. 1970). The aim was to extend aeration into areas of Australia where the climate is too warm for the use of ambient air to be effective. The concrete storage (with a capacity of 12 300 t of wheat) consisted of two identical units with each comprising one large central bin (24.4 m high, 10.3 m diameter and holding 1500 t) surrounded by eight smaller bins (each 24.4 m high, 6.4 m diameter and holding 580 t). A packaged refrigeration unit of about 10 kW cooling capacity (designed and built by CSIRO) was connected to two 580 t bins as shown in Figure 6. Ambient air was drawn through louvres and a wire screen into the evaporator and the condenser (Fig. 7). The evaporator (0.84 m by 0.48 m) consisted of 6 rows of 16 mm diameter copper tubes with aluminium

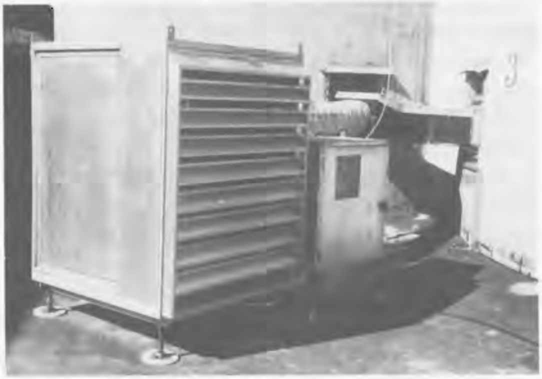

Fig. 6. Refrigerated aeration unit at Dalby, Queensland (connected to two 580 t silos).

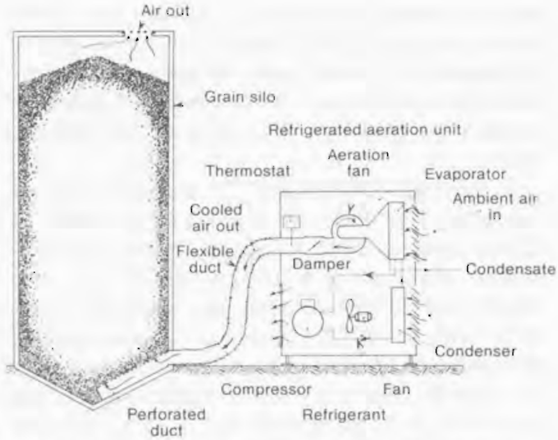

Fig. 7. Layout of refrigerated grain aeration system at Dalby, Queensland.

fins every 3 mm. Air from the evaporator passed through a 3.7 kW centrifugal fan and was discharged through a butterfly damper into the insulated aeration duct. The damper was controlled by a motor and thermostat so that the airflow rate was varied to keep the air temperature leaving the unit at about 10°C. Because of the heat added by the fan motor, the air relative humidity was reduced to below 80% for all rates of airflow. The refrigeration compressor was rated at 3.0 kW and used R22 refrigerant.

Results of three trials with wheat carried out over two seasons (Table 2) showed that insecticide-free wheat could be safely stored for 10 months, and that insect populations could be held at relatively low levels (Sutherland et al. 1970). The effect of low airflow rate and consequent inadequate cooling at the uninsulated walls of the silo was shown by the much higher infestation level in Trial No. 2. Although insect control was good in the other two trials, it was concluded that insulation or direct cooling of the silo walls would be necessary to render all parts of the grain bulk inhospitable to insects. The high electrical energy consumption of 34 kWh/t for Trial No. 1 was reduced to 18 kWh/t for Trial No. 3 by more

Table 2. Summary of results of three grain refrigerated aeration trials at Dalby, Queensland.

Trial No. Season	1 1967-68	2 1967-68	3 1968-69
Average airflow rate (L/sec/t of silo capacity)	0.45	0.15	0.6
Quantity of wheat (t)	594	594	570
Storage period (months)	10	10	10
Mean grain temperature (°C)			
Initial	26.4	33.0	28.3
Final	10.4	12.1	15.5
Time to cool to 15°C (months)	0.6	2.1	0.6
Mean grain moisture content (%, wet basis)			
Initial	10.8	10.7	11.1
Final	12.5	10.9	10.9
Total operating time (hours)	5600	5600	1900
Energy used (kWh/t of silo capacity)	34	11	18
Number of live insects			
Inloading	0	0	0
Outloading	0	35	3
Quantity of grain sieved (kg)			
Inloading	76	72	82
Outloading	214	94	91

Source: Elder et al. 1984.

selective operation of the refrigeration unit (1900 hours as against 5600 hours) by employing a thermostat to sense grain temperature. Grain moisture contents near the aeration duct were also reduced in Trial No. 3 as a result of reduced aeration.

Brookstead, Queensland. In the next trial of refrigerated aeration, at Brookstead in southern Queensland, a 5400 t capacity squat concrete-walled corrugated-iron roofed silo (9.6 m wall height and 28 m diameter) was insulated externally with a 50 mm thickness of spray-applied polyurethane foam covered with white paint (Fig. 8), with the object of maintaining all parts of the grain bulk to be refrigerated below 15°C (Elder et al. 1975, 1976). In the first experiment the existing aeration system was used to blow air through the grain. Return ducts were connected from the headspace to the two aeration fans to recirculate the air. The headspace air was cooled via a separate recirculation system comprising a belt-driven, double-inlet centrifugal fan (designed to deliver a flow rate of 5 m^3/sec against a pressure of 370 Pa) and a chilled brine 8-row cooling coil (2.1 m by 1.1 m with fins at 3 mm pitch) connected to a commercial chiller set of 70 kW nominal capacity (Fig. 9). The chiller incorporated two 11 kW compressors and two air-cooled condensers fitted with three 0.6 kW propellor fans. Each system was charged with 10 kg of Freon 22 and the brine passed through two shell-in-tube heat exchangers in series. The brine system comprised a 0.75 kW centrifugal pump circulating 390 kg of 22% by weight ethylene glycol solution through the chiller, cooling coil, mixing tank, orifice flow meter, and flow switch, via 50 mm diameter insulated P.V.C. pipes.

Fig. 8. Grain refrigerated aeration system on an insulated 5400 t squat silo at Brookstead, Queensland.

In the second and third seasons, the cooled air was again discharged into the roof space but was then drawn downwards through the grain, thereby filtering out the dust created during filling of the silo (Fig. 9). The existing linear aeration ducts were replaced by two concentric ducts (one at the perimeter of the silo and the other at ¼ radius) connected directly to the cooling system. Each duct could be operated independently so that cooling could start as soon as the central duct was covered with grain. In the system now in use the inner duct has been removed and the chilled air is passed directly to the perimeter duct. The air flows upwards through the grain and then back to the cooling circuit.

The main results obtained at Brookstead over three seasons are given in Table 3. Cooling to less than 15°C was achieved within two months, insect control was excellent, and grain quality was unaffected (Ghaly 1976). The perimeter duct on the floor of the silo installed after the first season enabled grain temperatures below 15°C to be achieved at the wall much earlier and through the hottest months. The average grain moisture content was increased by 0.4% in each season. The average monthly energy consumptions were 3.7, 3.3, and 2.8 kWh/t over respective storage periods of 6, 9, and 10 months. The total capital cost of the system, in 1973, was $A7.40/t ($A2.60/t for insulation), and the electricity cost over six months was about 50 cents/t. The third trial was conducted using malting barley instead of wheat, and the enhanced germination and malt yield resulting from storage in the refrigerated silo has led to continued commercial use of the system for barley.

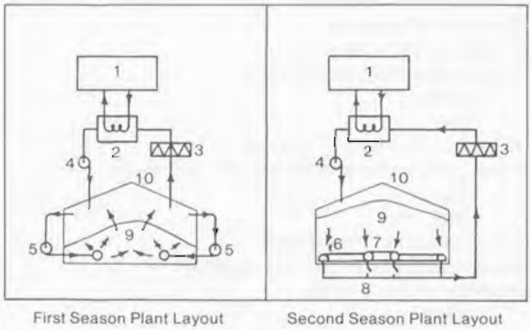

Fig. 9. Grain refrigeration system layouts at Brookstead, Queensland: 1. chiller; 2. cooling coil; 3. air filter; 4. fan; 5. original aeration system with recirculation duct added; 6. perimeter duct; 7. central duct; 8. duct gates; 9. grain; 10. silo.

Table 3. Summary of results of three grain refrigerated aeration trials at Brookstead, Queensland.

Trial No. Season	1 1973-74	2 1974-75	3 1975-76
Average airflow rate (L/sec/t of silo capacity)	0.8	0.8	0.9
Quantity of wheat (t)	2390	5230	2230
Storage period (months)	6	9	10
Mean grain temperature (°C)			
Initial	29	27	26
Final	6	5	8
Time to cool to 15°C (months)	1.7	1.2	1.4
Mean grain moisture content (%, wet basis)			
Initial	11.0	11.2	11.3
Final	11.4	11.6	11.7
Energy used (kWh/t of silo capacity)	22	30	28
Number of live insects			
Inloading	17	1	6
Outloading	1	0	0
Quantity of grain sieved (kg)			
Inloading	384	543	255
Outloading	490	863	429

Source: Elder et al. 1984.

Lah, Victoria. The refrigerated aeration system applied to a 1700 t wheat silo at Lah in north-western Victoria (Fig. 10) was designed on the basis of computer simulation (Thorpe 1976) and the practical experience gained in Queensland (Hunter and Taylor 1980). The theoretical work showed that recirculation systems gave much lower annual costs than systems such as that at Dalby in which the air from the silo is exhausted to atmosphere. The steel silo (13.1 m wall height and 14.5 m diameter) was thermally insulated with polyurethane foam sprayed externally to a nominal thickness of 25 mm on the roof and 50 mm on the wall. The foam was protected against ultraviolet degradation by an expansive elastomeric hypalon coating. The system comprised a self-

Fig. 10. Refrigerated aeration system on a 1700 t silo at Lah, Victoria.

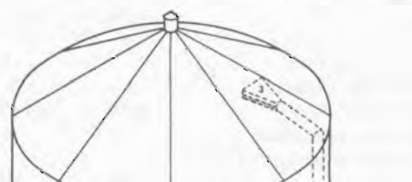

Fig. 11. Diagram of Lah grain refrigeration system: 1. refrigeration unit; 2. atmospheric air intake; 3. return air intake; 4. perforated air distribution duct.

contained refrigeration unit with a direct-expansion air-cooling coil connected to distribution ducting around the periphery of the site floor and a recirculation duct from the headspace (Fig. 11).

The refrigeration unit had a cooling capacity of 34 kW (i.e. 20 W per tonne of silo nominal capacity) and used a 7.5 kW compressor. The cooled air was supplied via a 7.5 kW fan through perforated half-round ducting (0.57 m diameter) arranged in a 12-sided figure on the floor of the silo as close as possible to the silo wall (Fig. 11). Return air was drawn from one side of the headspace into a circular duct (0.57 m diameter) located inside the silo. A damper and T-piece were installed in the return duct just upstream of the refrigeration unit so that atmospheric air could be drawn into the unit at inloading to overcome dust problems, and to allow the initially hot return air to be expelled. The loading hatch at the apex of the silo was left open to the atmosphere. The control circuit had thermostats to cope with defrosting the coil, to switch off the compressor when the temperature of the return air fell to 8°C, and to switch off both the compressor and the fan when the return air and ambient air temperatures were both below 11°C.

Results of two trials at Lah with unsprayed wheat (summarised in Table 4) showed that

Table 4. Summary of results of two grain refrigerated aeration trials at Lah, Victoria.

Trial No.	1	2
Season	1976-77	1977-78
Average airflow rate (L/sec/t of silo capacity)	1.5	1.5
Quantity of wheat (t)	1650	1750
Storage period (months)	9	5
Mean grain temperature (°C)		
Initial	34	30
Final	9	9
Time to cool to 15°C (months)	1.2	1.4
Mean grain moisture content (%, wet basis)		
Initial	8.8	8.3
Final	9.2	8.8
Energy used (kWh/t of silo capacity)	24	22
Number of live insects		
Inloading	0	0
Outloading	0	0
Quantity of grain sieved (kg)		
Inloading	276	271
Outloading	204	210

Source: Elder et al. 1984.

adequate insect control temperatures were achieved, energy cost was comparable to that of new protectant insecticides, and that the peripheral duct satisfactorily cooled the central grain and peak of the bulk, as well as the grain near the silo wall (Hunter and Taylor 1980). No live insects were found at either inloading or outloading of the wheat. The capital cost of the refrigerated aeration system in 1976 ws $A17.05/t of which 43% was for the thermal insulation.

Gravesend, New South Wales. The ability of a direct-expansion refrigeration system and continuous airflow through the grain at the silo wall to provide adequate cooling performance (as at Lah) led to a concept of modular cooling units of a standard design to suit all types of grain stores (Elder 1980). Six such modified commercial air-conditioning units were installed along the south-western wall of a horizontal shed store (with a capacity of 15 000 t of wheat) at Gravesend in the northern wheat belt of New South Wales (Fig. 12). The store (96 m long by 24 m wide and 6 m wall height) comprised a concrete floor, steel grain retaining walls, and corrugated-iron gable roof. The openings at the eaves were closed off by fitting sheets of iron vertically from the top of the 6 m high grain retaining wall to the roof along the side walls, and at an angle so as to shed grain from the gable ends. The whole structure was insulated externally with 25 mm of polyurethane foam on the roof and 50 mm on the retaining walls, the insulation being covered by a white hypalon mastic coating.

Each refrigeration unit (servicing 2500 t of wheat) recirculated air drawn from above the grain surface and delivered it cooled to half-round perforated ducts (0.8 m diameter) around the periphery of the shed floor (Fig. 13). The coil of

Fig. 12. Refrigerated aeration system on a 15 000 t grain shed at Gravesend, New South Wales.

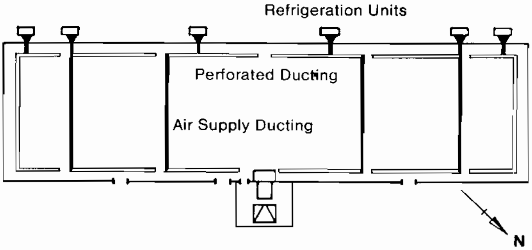

Fig. 13. Layout of refrigeration units and ducting in the Gravesend grain shed.

each unit had a cooling capacity of 30 kW. The power absorbed by the refrigeration condensing system and the refrigerated air recirculation fan in each unit averaged 13 kW at near full capacity in summer and 6 kW in winter.

The trials carried out at Gravesend on unsprayed wheat are described in detail by Elder and Ghaly (1984) and Elder et al. (1984) and some typical results are given in Table 5. In the 1977–78 season, the airflow rate was substantially lower than the design value, and it took three months for the average grain temperature to fall from 32 to 15°C. Nevertheless, good insect control was achieved although low insect populations could be found at the peaks of the grain surface. The average wheat moisture content increased by 1.1% (wet basis), and electricity consumption averaged 2.6 kWh/t/month. The capital cost of the system in 1977 was $A14.50/t, of which insulation accounted for 40%. In 1980–81, although the airflow rate was at the design value, the shed was only 30% full and the wheat was in three separate heaps. Insect control was reasonable, even though the wheat took 4.5 months to cool from 28 to 15°C.

Table 5. Summary of results of two grain refrigerated aeration trials at Gravesend, New South Wales.

Trial No. Season	1 1977-78	2 1980-81
Average airflow rate (L/sec/t of silo capacity)	0.7	1.0
Quantity of wheat (t)	12 160	4335
Storage period (months)	10	10
Mean grain temperature (°C)		
Initial	32	28
Final	9	12
Time to cool to 15°C (months)	2.9	4.5
Mean grain moisture content (%, wet basis)		
Initial	9.9	10.9
Final	11.0	11.8
Energy used (kWh/t of silo capacity)	26	29
Number of live insects		
Inloading	0	5
Outloading	5	19
Quantity of grain sieved (kg)		
Inloading	968	404
Outloading	1016	340

Source: Elder et al. 1984.

Combined Grain Cooling and Pesticide Treatment

A theoretical study by Thorpe and Elder (1982) showed that cooling of grain slowed down the rate of degradation of chemical pesticides applied to the grain. This study was confirmed by some experiments at Murtoa (north-western Victoria) in 1980 using fenitrothion (Hunter 1981). In the temperate and sub-tropical wheat-growing regions of Australia, aeration can reduce amounts of the pesticide methacrifos applied by factors of 7 and 4, respectively (Thorpe and Elder 1982). Further confirmation of this phenomenon was obtained in the experiments using malathion at Murtoa and Rainbow which were described earlier.

The combined use of cooling (with either ambient air or chilled air) and insecticides can be achieved in a number of ways. Refrigerated aeration could be used in uninsulated grain stores in addition to a low dosage of insecticide that would kill pests which could otherwise breed in warm grain near the walls and floor of the store. The insecticide would provide protection from reinfestation when the grain was outloaded from the store. Capital costs would be lower because of the absence of thermal insulation which accounts for about 40% of the total cost of the cooling system. As an alternative, grain could be cooled rapidly to 20°C, at which temperature the rate of reproduction of most insects is retarded, and a smaller dose of insecticide applied. Because of the decreased degradation of the insecticide at the lower temperature, the grain could then be held without further cooling.

Aeration of High Moisture Content Grain

Ardrossan, South Australia. It was shown in a trial at Ardrossan, South Australia in 1966 that aeration enabled barley to be stored safely at a higher moisture content than usual (Doolette and Sanders 1966). The trial was conducted in two vertical concrete silos (28.3 m high, 10.7 m diameter, and having a capacity of 1700 t of barley). The silos were filled with barley having average moisture contents of 12 and 14% (wet basis), and aeration was in a downwards direction at a flow rate of 1.0 L/sec/t. It was found that after storage for nine months there were no measurable differences in quality in the barley in both silos. After 1150 hours of aeration the mean grain temperatures were 8°C (in the silo containing 14% moisture content barley) and 10°C (in the silo containing 12% moisture content barley).

Biloela, Queensland. A trial of aeration of grain sorghum of 16% moisture content was carried out at Biloela, near Gladstone in Queensland in 1977 (W.B. Elder, pers. comm.). Two farm silos each of 100 t capacity (3.4 m wall height and 5.8 m diameter) were used. A CSIRO farm aeration unit was connected to a full-round perforated duct (3.0 m long and 0.15 m diameter) positioned along the sloping floor of one silo, and the other silo was left unaerated. The sorghum temperature in the centre of the aerated silo decreased from 31 to 23°C in one month (after about 400 hours of aeration), whereas the unaerated silo centre temperature increased from 31 to 50°C in two weeks as a result of respiration heating. The average sorghum moisture content changed from 15.8 to 15.2% in the aerated silo and from 15.7 to 15.9% in the unaerated silo. The germination percentage changed from 92 to 89% in the aerated bin and to 80% in the unaerated bin. No mould was detected, but the unaerated sorghum had an unpleasant odour on outloading. Aflatoxins were detected in the unaerated bin but not in the aerated bin. This trial showed that grain sorghum can be stored safely for limited periods under aeration while waiting to be dried. This practice is now in commercial use in large aerated silos at Gladstone, before the sorghum is dried in a large tower dryer.

Solar Grain Cooling for the Humid Tropics

In temperate climates, ambient air is often of sufficiently low temperature and enthalpy to provide effective cooling of a grain bulk. However, in tropical climates, which are characterised by hot and humid ambient air conditions, the amount of grain cooling achievable may be inadequate to prevent loss of grain quality. In this case, lower grain temperatures can be achieved by reducing the enthalpy of the ambient air by isothermally lowering its absolute humidity before passing it into the grain bed. This can be carried out in an open-cycle, solar-regenerated, desiccant-bed grain

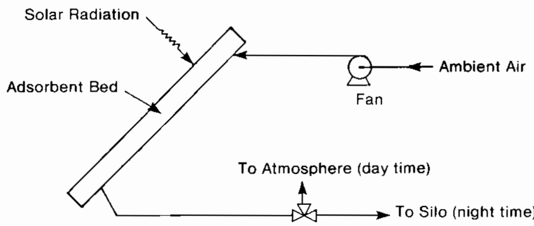

Fig. 14. Schematic arrangement of components in the adsorbent-bed grain cooling system.

cooling system (Thorpe 1981; Thorpe and Fricke, 1985).

The principle of operation of this device, which can be employed in single or multiple stages, is shown in Figure 14. During the night, ambient air is blown through a narrow bed of dry desiccant material so that the heat of sorption can be readily dissipated to atmosphere, and the air of reduced enthalpy is passed into the grain. The desiccant becomes wet, but it is dried during the day by solar radiation falling on the desiccant bed and the simultaneous passage of air through it. During the regeneration process (daytime) the air leaving the adsorbent bed is expelled to atmosphere.

Experiments have shown that by using the solar cooling system, grain temperatures up to 10°C lower than that produced by normal ambient aeration can be achieved (Thorpe 1981). The system is easily built from sheet metal, has no more moving parts than a conventional grain aeration system, can use seed grains as the adsorbent, and ensures drier grain.

Discussion and Conclusions

Trials of a variety of aeration systems using both ambient and refrigerated air have been described. The trials used a mixture of upwards and downwards airflow, and manual and automatic control. In general, upwards flow aeration is now preferred, mainly because the heat of compression added by the aeration fan reduces the relative humidity of the air entering the grain bed. This can remove the need for a humidistat control and restrict the moisture content of the grain near the aeration duct.

When aeration began in Australia, control of fan operation was performed by manual setting of temperature and humidity limits on the ambient air. Also, it was shown by Griffiths (1967) that wet-bulb temperature control was preferable to dry-bulb temperature control, as the temperature reached by the grain is dependent on the air wet-

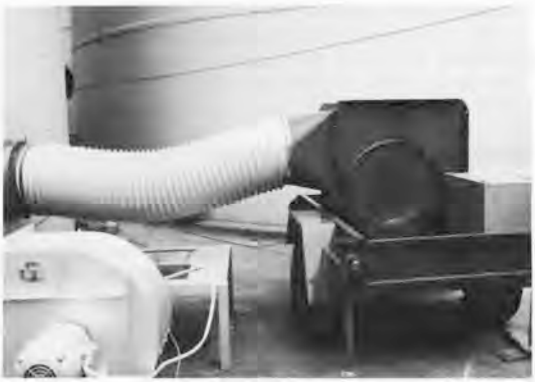

Fig. 15. Mobile unit for natural aeration of grain.

Fig. 16. Mobile unit for refrigerated aeration of grain.

bulb temperature and the grain moisture content. However, this practice of manual setting of limits made supervision of operation at remote country sites difficult. A number of other controller types, e.g. temperature difference and time switch have been tried, but almost all new aeration systems now installed in Australia use the CSIRO time-proportioning controller (Elder 1972). This controller requires no operator intervention, and automatically selects the coldest periods for aeration fan operation by means of a thermostat which winds down when the fan is running and winds up when the fan is not running. The controller has a rapid setting which ensures operation for 12 hours per day on average and a normal setting which allows 15 hours per week on average. The time-proportioning controller is now commercially available in Australia in both electro-mechanical and electronic forms.

The aeration systems described in this paper have all been fixed. However, mobile grain cooling units are quite possible and a few, using both ambient and refrigerated air, are in use in Australia (Figs 15 and 16). Both the units shown are mounted on trailers and are designed to cool 2000 t of wheat at airflow rates from 1.0 to 1.5 L/sec/t. They use 10 kW centrifugal fans and the mobile refrigerated aeration unit (Fig. 16) has a cooling capacity of 44 kW. The capital costs, in 1980, were about $A2500 for the mobile natural aeration unit and $A15 000 for the mobile refrigerated aeration unit (Hunter 1981).

In general, any degree of grain cooling achieved by aeration is beneficial to the grain, and thus even in the humid tropics aeration can be recommended as a worthwhile method of reducing grain storage problems. In these climates, a technique which would reduce the enthalpy of the ambient air, such as the solar grain cooler described in this paper or some form of dehumidifier, would of course be beneficial.

Acknowledgments

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sampling that careful sieving uncovered a few live secondary insects, mainly at the peak of the bulk. No insects were found on outloading the silos even though no insecticide had been applied to the wheat. In a test on an unaerated bin, insect numbers increased, giving rise to a steep temperature gradient near the grain surface. The capital cost of the complete aeration system was $A16 000 ($A1.70 per tonne of store capacity), and the running cost was estimated to be 5 cents/t of wheat.

Murtoa, Victoria. The first trial of aeration combined with insecticide (malathion) treatment in Australia was carried out at Murtoa in north-western Victoria in 1965 (Sutherland 1966b). The storage (Fig. 2) holding 22 400 t of barley consisted of 14 steel silos (14.9 m wall height and 14.5 m diameter with a capacity of 1600 t of barley). Each bin had two half-round perforated ducts (4.6 m long and 0.8 m diameter) along the hopper bottom, connected to a non-overloading centrifugal fan, direct-coupled to a 3.7 kW motor. The design airflow rate was 1.0 L/sec/t of barley, and wet-bulb temperature and relative humidity control was employed.

Aeration in two bins (one with upwards airflow and the other downwards) reduced malting barley temperatures to 8°C after 1200 hours of aeration in eight months of storage. No insects were found, and cooling of the grain prolonged the life of the malathion, which has been found to degrade rapidly above 20°C and 12% moisture content (Minett et al. 1968). The capital cost of the complete aeration system was about $A24 000 ($A1.10 per tonne of store capacity). The running cost was 5 cents/t (0.4 cents/t per 100 hours of aeration) which was comparable with the cost of application of malathion spray at 12 parts per million.

In a further aeration trial at Murtoa in 1966 on two bins of unsprayed wheat, one was cooled from 30°C to 10°C after 1100 hours of aeration in eight months and the other was cooled from 27 to 10°C after 1000 hours of aeration in eight months (Elder and Sutherland 1970).

Rainbow, Victoria. Another trial of aeration combined with malathion treatment was carried out at Rainbow in north-western Victoria in 1967 (Sutherland and Elder 1969). For this 3400 t barley storage (Fig. 3) each of the two large concrete bins (25.9 m high, 10.7 m diameter and holding 1360 t) was fitted with a 4.1 kW two-stage axial fan, and each of the two small concrete bins (25.9 m high, 5.5 m diameter and holding 340 t) was fitted with a 2.2 kW centrifugal blower. Submerged aeration ducts (V-shaped in plan) were used being 7.8 m long and 0.8 m wide (each leg of V) in the large bins and 3.4 m long and 0.4 m wide in the small bins. The design airflow rate was 1.0 L/sec/t of barley. Aeration was in a downwards direction and controlled by a high wet-bulb temperature limit and a high relative humidity limit. The relative humidity control was achieved by measurement of the wet-bulb depression of the air and not by the use of hair elements as in the previous systems.

In one large bin, the average centreline temperature was reduced from 30 to 13°C after 1200 hours of aeration in seven months. In the other large bin, the average temperature fell from 26 to 13°C after 1070 hours in eight months. Average barley moisture contents remained unchanged, there was no drop in germination percentage, and no insects were found during inspection at the peak of the bulk, through the bulk, and on outloading.

Kingaroy, Queensland. A trial aeration of peanuts-in-shell was carried out at Kingaroy in southern Queensland over two seasons (1970-71 and 1971-72). Three concrete bins (26 m high, 6 m diameter, and holding 170 t of peanuts-in-shell) were each fitted with a 0.6 kW axial fan giving an airflow rate of 2.5 L/sec/t.

All the fans were connected to a CSIRO time-proportioning aeration controller (Elder 1972).

Aeration combined with malathion application kept the peanuts-in-shell in good condition for a storage period of 10 months (Ghaly 1978). Analysis of bulk samples showed the average infestation level of the aerated bins to be significantly less that that of the unaerated bins. Free fatty acid content was also less in the aerated bins. There were no significant differences in viability and appearance of the kernels between aerated and unaerated peanuts.

FARM STORES

Albury, New South Wales. Two steel farm silos holding 28 and 44 t of oats were aerated for a period of two years (1969 and 1970) using two outlets of a 0.4 kW CSIRO farm aeration unit (Fig. 4) at Albury in southern New South Wales (Elder 1969). The silos had a wall height of 4.5 m, with the larger one having a diameter of 4.9 m and the smaller one 4.0 m (Fig. 5). Two full-round aeration ducts (each 2.4 m long and 0.15 m diameter) were

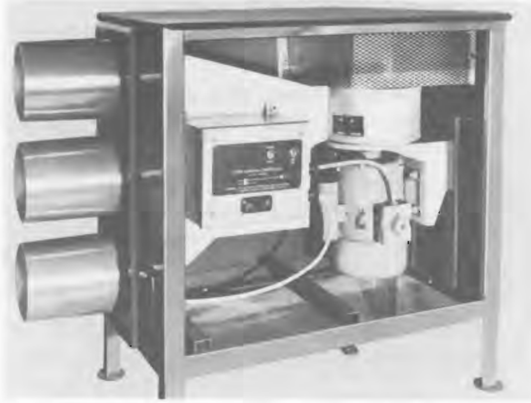

Fig. 4. CSIRO unit for farm aeration of grain.

Fig. 5. Steel farms silos at Albury, New South Wales (28 and 44 t of oats).

placed along the hopper bottom of the larger silo, and one duct (2.0 m long and 0.15 m diameter) supplied the smaller silo. The design airflow rate was 1.6 L/sec/t of oats.

The oats in both silos were kept in good condition even though no chemical treatment was applied (Elder 1971). The average centreline temperatures were kept between 8 and 18°C, apart apart from the first three months after harvest. Grain temperatures near the north wall remained high enough to permit some insect reproduction for much of the storage period. This was partly offset by some drying of the grain near the walls, as a result of repeated conduction heating and aeration cooling. The level of insect infestation was kept under control, although there was a large seasonal variation. Insects generally congregate at the peak of the grain bulk where they are accessible for chemical treatment if required. The moisture content of the oats reached 13% (wet basis) near the aeration ducts in both bins, and the average increased from 10 to 11%. Germination tests showed no deterioration in quality after two years storage.

Dookie, Victoria, Aeration of two steel farm silos, each having a capacity of 54 t of wheat, was performed at a flow rate of 2 L/sec/t using a CSIRO farm aeration unit and controller at Dookie in north-eastern Victoria. The flat-bottomed bins were 4.5 m diameter and had a wall height of 4.5 m. The full-round aeration ducts were 3.7 m long and 0.15 m in diameter.

In the first trial (1969-70), unsprayed wheat of 11% moisture content was stored successfully under aeration for 18 months, whereas an unaerated bin had to be fumigated. Wheat temperatures were reduced from 27 to 18°C in three months in the aerated bins (Williams and Elder 1979). The number of insects found in the control silo at outloading was 70 times the number (live plus dead) in one of the aerated silos. The other aerated silo was exposed to the heat of the sun and became infested at the north-western wall.

Greater cooling at the north-western wall of the exposed silo was achieved in a second trial (1971-72), by placing the aeration duct in the north-western sector of the bin floor (Ghaly 1984). This suppressed insect numbers to the same level as for the partly shaded silo. After four months of aeration, the average wheat temperatures at the centre of the silos ranged from 11 to 21°C for the next 14 months. The average wheat moisture contents increased by 2% as a result of aeration.

Refrigerated Aeration in Large Stores

Dalby, Queensland. The first refrigerated aeration system for grain in Australia was installed at Dalby, southern Queensland in 1967 (Sutherland et al. 1970). The aim was to extend aeration into areas of Australia where the climate is too warm for the use of ambient air to be effective. The concrete storage (with a capacity of 12 300 t of wheat) consisted of two identical units with each comprising one large central bin (24.4 m high, 10.3 m diameter and holding 1500 t) surrounded by eight smaller bins (each 24.4 m high, 6.4 m diameter and holding 580 t). A packaged refrigeration unit of about 10 kW cooling capacity (designed and built by CSIRO) was connected to two 580 t bins as shown in Figure 6. Ambient air was drawn through louvres and a wire screen into the evaporator and the condenser (Fig. 7). The evaporator (0.84 m by 0.48 m) consisted of 6 rows of 16 mm diameter copper tubes with aluminium

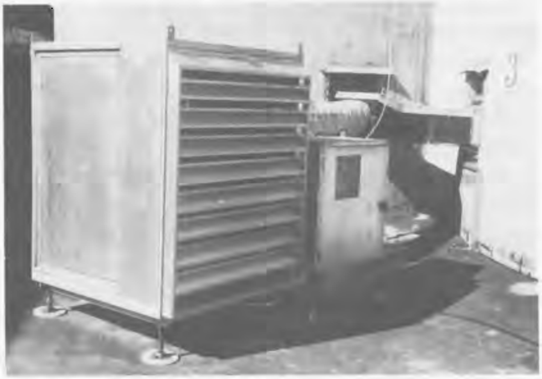

Fig. 6. Refrigerated aeration unit at Dalby, Queensland (connected to two 580 t silos).

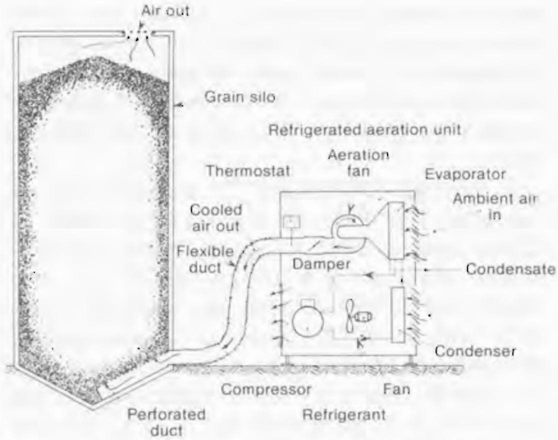

Fig. 7. Layout of refrigerated grain aeration system at Dalby, Queensland.

fins every 3 mm. Air from the evaporator passed through a 3.7 kW centrifugal fan and was discharged through a butterfly damper into the insulated aeration duct. The damper was controlled by a motor and thermostat so that the airflow rate was varied to keep the air temperature leaving the unit at about 10°C. Because of the heat added by the fan motor, the air relative humidity was reduced to below 80% for all rates of airflow. The refrigeration compressor was rated at 3.0 kW and used R22 refrigerant.

Results of three trials with wheat carried out over two seasons (Table 2) showed that insecticide-free wheat could be safely stored for 10 months, and that insect populations could be held at relatively low levels (Sutherland et al. 1970). The effect of low airflow rate and consequent inadequate cooling at the uninsulated walls of the silo was shown by the much higher infestation level in Trial No. 2. Although insect control was good in the other two trials, it was concluded that insulation or direct cooling of the silo walls would be necessary to render all parts of the grain bulk inhospitable to insects. The high electrical energy consumption of 34 kWh/t for Trial No. 1 was reduced to 18 kWh/t for Trial No. 3 by more

Table 2. Summary of results of three grain refrigerated aeration trials at Dalby, Queensland.

Trial No. Season	1 1967-68	2 1967-68	3 1968-69
Average airflow rate (L/sec/t of silo capacity)	0.45	0.15	0.6
Quantity of wheat (t)	594	594	570
Storage period (months)	10	10	10
Mean grain temperature (°C)			
Initial	26.4	33.0	28.3
Final	10.4	12.1	15.5
Time to cool to 15°C (months)	0.6	2.1	0.6
Mean grain moisture content (%, wet basis)			
Initial	10.8	10.7	11.1
Final	12.5	10.9	10.9
Total operating time (hours)	5600	5600	1900
Energy used (kWh/t of silo capacity)	34	11	18
Number of live insects			
Inloading	0	0	0
Outloading	0	35	3
Quantity of grain sieved (kg)			
Inloading	76	72	82
Outloading	214	94	91

Source: Elder et al. 1984.

selective operation of the refrigeration unit (1900 hours as against 5600 hours) by employing a thermostat to sense grain temperature. Grain moisture contents near the aeration duct were also reduced in Trial No. 3 as a result of reduced aeration.

Brookstead, Queensland. In the next trial of refrigerated aeration, at Brookstead in southern Queensland, a 5400 t capacity squat concrete-walled corrugated-iron roofed silo (9.6 m wall height and 28 m diameter) was insulated externally with a 50 mm thickness of spray-applied polyurethane foam covered with white paint (Fig. 8), with the object of maintaining all parts of the grain bulk to be refrigerated below 15°C (Elder et al. 1975, 1976). In the first experiment the existing aeration system was used to blow air through the grain. Return ducts were connected from the headspace to the two aeration fans to recirculate the air. The headspace air was cooled via a separate recirculation system comprising a belt-driven, double-inlet centrifugal fan (designed to deliver a flow rate of 5 m^3/sec against a pressure of 370 Pa) and a chilled brine 8-row cooling coil (2.1 m by 1.1 m with fins at 3 mm pitch) connected to a commercial chiller set of 70 kW nominal capacity (Fig. 9). The chiller incorporated two 11 kW compressors and two air-cooled condensers fitted with three 0.6 kW propellor fans. Each system was charged with 10 kg of Freon 22 and the brine passed through two shell-in-tube heat exchangers in series. The brine system comprised a 0.75 kW centrifugal pump circulating 390 kg of 22% by weight ethylene glycol solution through the chiller, cooling coil, mixing tank, orifice flow meter, and flow switch, via 50 mm diameter insulated P.V.C. pipes.

Fig. 8. Grain refrigerated aeration system on an insulated 5400 t squat silo at Brookstead, Queensland.

In the second and third seasons, the cooled air was again discharged into the roof space but was then drawn downwards through the grain, thereby filtering out the dust created during filling of the silo (Fig. 9). The existing linear aeration ducts were replaced by two concentric ducts (one at the perimeter of the silo and the other at ¼ radius) connected directly to the cooling system. Each duct could be operated independently so that cooling could start as soon as the central duct was covered with grain. In the system now in use the inner duct has been removed and the chilled air is passed directly to the perimeter duct. The air flows upwards through the grain and then back to the cooling circuit.

The main results obtained at Brookstead over three seasons are given in Table 3. Cooling to less than 15°C was achieved within two months, insect control was excellent, and grain quality was unaffected (Ghaly 1976). The perimeter duct on the floor of the silo installed after the first season enabled grain temperatures below 15°C to be achieved at the wall much earlier and through the hottest months. The average grain moisture content was increased by 0.4% in each season. The average monthly energy consumptions were 3.7, 3.3, and 2.8 kWh/t over respective storage periods of 6, 9, and 10 months. The total capital cost of the system, in 1973, was $A7.40/t ($A2.60/t for insulation), and the electricity cost over six months was about 50 cents/t. The third trial was conducted using malting barley instead of wheat, and the enhanced germination and malt yield resulting from storage in the refrigerated silo has led to continued commercial use of the system for barley.

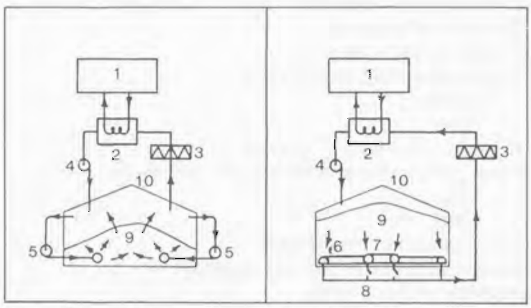

Fig. 9. Grain refrigeration system layouts at Brookstead, Queensland: 1. chiller; 2. cooling coil; 3. air filter; 4. fan; 5. original aeration system with recirculation duct added; 6. perimeter duct; 7. central duct; 8. duct gates; 9. grain; 10. silo.

Table 3. Summary of results of three grain refrigerated aeration trials at Brookstead, Queensland.

Trial No. Season	1 1973-74	2 1974-75	3 1975-76
Average airflow rate (L/sec/t of silo capacity)	0.8	0.8	0.9
Quantity of wheat (t)	2390	5230	2230
Storage period (months)	6	9	10
Mean grain temperature (°C)			
Initial	29	27	26
Final	6	5	8
Time to cool to 15°C (months)	1.7	1.2	1.4
Mean grain moisture content (%, wet basis)			
Initial	11.0	11.2	11.3
Final	11.4	11.6	11.7
Energy used (kWh/t of silo capacity)	22	30	28
Number of live insects			
Inloading	17	1	6
Outloading	1	0	0
Quantity of grain sieved (kg)			
Inloading	384	543	255
Outloading	490	863	429

Source: Elder et al. 1984.

Lah, Victoria. The refrigerated aeration system applied to a 1700 t wheat silo at Lah in north-western Victoria (Fig. 10) was designed on the basis of computer simulation (Thorpe 1976) and the practical experience gained in Queensland (Hunter and Taylor 1980). The theoretical work showed that recirculation systems gave much lower annual costs than systems such as that at Dalby in which the air from the silo is exhausted to atmosphere. The steel silo (13.1 m wall height and 14.5 m diameter) was thermally insulated with polyurethane foam sprayed externally to a nominal thickness of 25 mm on the roof and 50 mm on the wall. The foam was protected against ultraviolet degradation by an expansive elastomeric hypalon coating. The system comprised a self-

Fig. 10. Refrigerated aeration system on a 1700 t silo at Lah, Victoria.

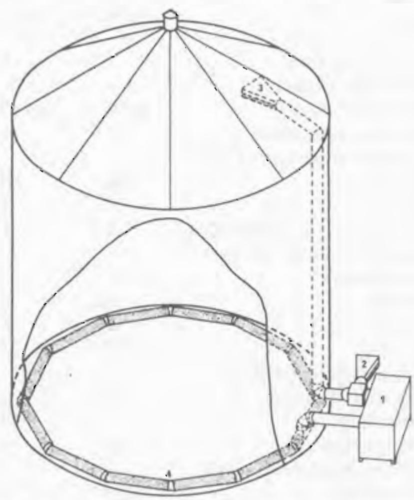

Fig. 11. Diagram of Lah grain refrigeration system: 1. refrigeration unit; 2. atmospheric air intake; 3. return air intake; 4. perforated air distribution duct.

contained refrigeration unit with a direct-expansion air-cooling coil connected to distribution ducting around the periphery of the site floor and a recirculation duct from the headspace (Fig. 11).

The refrigeration unit had a cooling capacity of 34 kW (i.e. 20 W per tonne of silo nominal capacity) and used a 7.5 kW compressor. The cooled air was supplied via a 7.5 kW fan through perforated half-round ducting (0.57 m diameter) arranged in a 12-sided figure on the floor of the silo as close as possible to the silo wall (Fig. 11). Return air was drawn from one side of the headspace into a circular duct (0.57 m diameter) located inside the silo. A damper and T-piece were installed in the return duct just upstream of the refrigeration unit so that atmospheric air could be drawn into the unit at inloading to overcome dust problems, and to allow the initially hot return air to be expelled. The loading hatch at the apex of the silo was left open to the atmosphere. The control circuit had thermostats to cope with defrosting the coil, to switch off the compressor when the temperature of the return air fell to 8°C, and to switch off both the compressor and the fan when the return air and ambient air temperatures were both below 11°C.

Results of two trials at Lah with unsprayed wheat (summarised in Table 4) showed that adequate insect control temperatures were achieved, energy cost was comparable to that of new protectant insecticides, and that the peripheral duct satisfactorily cooled the central grain and peak of the bulk, as well as the grain near the silo wall (Hunter and Taylor 1980). No live insects were found at either inloading or outloading of the wheat. The capital cost of the refrigerated aeration system in 1976 ws $A17.05/t of which 43% was for the thermal insulation.

Table 4. Summary of results of two grain refrigerated aeration trials at Lah, Victoria.

Trial No. Season	1 1976-77	2 1977-78
Average airflow rate (L/sec/t of silo capacity)	1.5	1.5
Quantity of wheat (t)	1650	1750
Storage period (months)	9	5
Mean grain temperature (°C)		
Initial	34	30
Final	9	9
Time to cool to 15°C (months)	1.2	1.4
Mean grain moisture content (%, wet basis)		
Initial	8.8	8.3
Final	9.2	8.8
Energy used (kWh/t of silo capacity)	24	22
Number of live insects		
Inloading	0	0
Outloading	0	0
Quantity of grain sieved (kg)		
Inloading	276	271
Outloading	204	210

Source: Elder et al. 1984.

Gravesend, New South Wales. The ability of a direct-expansion refrigeration system and continuous airflow through the grain at the silo wall to provide adequate cooling performance (as at Lah) led to a concept of modular cooling units of a standard design to suit all types of grain stores (Elder 1980). Six such modified commercial air-conditioning units were installed along the south-western wall of a horizontal shed store (with a capacity of 15 000 t of wheat) at Gravesend in the northern wheat belt of New South Wales (Fig. 12). The store (96 m long by 24 m wide and 6 m wall height) comprised a concrete floor, steel grain retaining walls, and corrugated-iron gable roof. The openings at the eaves were closed off by fitting sheets of iron vertically from the top of the 6 m high grain retaining wall to the roof along the side walls, and at an angle so as to shed grain from the gable ends. The whole structure was insulated externally with 25 mm of polyurethane foam on the roof and 50 mm on the retaining walls, the insulation being covered by a white hypalon mastic coating.

Each refrigeration unit (servicing 2500 t of wheat) recirculated air drawn from above the grain surface and delivered it cooled to half-round perforated ducts (0.8 m diameter) around the periphery of the shed floor (Fig. 13). The coil of

Fig. 12. Refrigerated aeration system on a 15 000 t grain shed at Gravesend, New South Wales.

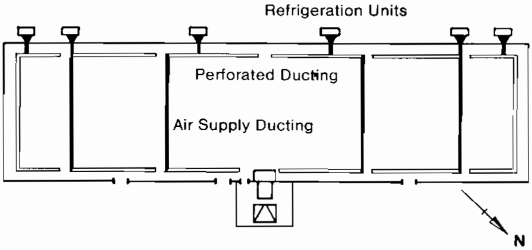

Fig. 13. Layout of refrigeration units and ducting in the Gravesend grain shed.

each unit had a cooling capacity of 30 kW. The power absorbed by the refrigeration condensing system and the refrigerated air recirculation fan in each unit averaged 13 kW at near full capacity in summer and 6 kW in winter.

The trials carried out at Gravesend on unsprayed wheat are described in detail by Elder and Ghaly (1984) and Elder et al. (1984) and some typical results are given in Table 5. In the 1977–78 season, the airflow rate was substantially lower than the design value, and it took three months for the average grain temperature to fall from 32 to 15°C. Nevertheless, good insect control was achieved although low insect populations could be found at the peaks of the grain surface. The average wheat moisture content increased by 1.1% (wet basis), and electricity consumption averaged 2.6

Table 5. Summary of results of two grain refrigerated aeration trials at Gravesend, New South Wales.

Trial No. Season	1 1977-78	2 1980-81
Average airflow rate (L/sec/t of silo capacity)	0.7	1.0
Quantity of wheat (t)	12 160	4335
Storage period (months)	10	10
Mean grain temperature (°C)		
Initial	32	28
Final	9	12
Time to cool to 15°C (months)	2.9	4.5
Mean grain moisture content (%, wet basis)		
Initial	9.9	10.9
Final	11.0	11.8
Energy used (kWh/t of silo capacity)	26	29
Number of live insects		
Inloading	0	5
Outloading	5	19
Quantity of grain sieved (kg)		
Inloading	968	404
Outloading	1016	340

Source: Elder et al. 1984.

kWh/t/month. The capital cost of the system in 1977 was $A14.50/t, of which insulation accounted for 40%. In 1980–81, although the airflow rate was at the design value, the shed was only 30% full and the wheat was in three separate heaps. Insect control was reasonable, even though the wheat took 4.5 months to cool from 28 to 15°C.

Combined Grain Cooling and Pesticide Treatment

A theoretical study by Thorpe and Elder (1982) showed that cooling of grain slowed down the rate of degradation of chemical pesticides applied to the grain. This study was confirmed by some experiments at Murtoa (north-western Victoria) in 1980 using fenitrothion (Hunter 1981). In the temperate and sub-tropical wheat-growing regions of Australia, aeration can reduce amounts of the pesticide methacrifos applied by factors of 7 and 4, respectively (Thorpe and Elder 1982). Further confirmation of this phenomenon was obtained in the experiments using malathion at Murtoa and Rainbow which were described earlier.

The combined use of cooling (with either ambient air or chilled air) and insecticides can be achieved in a number of ways. Refrigerated aeration could be used in uninsulated grain stores in addition to a low dosage of insecticide that would kill pests which could otherwise breed in warm grain near the walls and floor of the store. The insecticide would provide protection from reinfestation when the grain was outloaded from the store. Capital costs would be lower because of the absence of thermal insulation which accounts for about 40% of the total cost of the cooling system. As an alternative, grain could be cooled rapidly to 20°C, at which temperature the rate of reproduction of most insects is retarded, and a smaller dose of insecticide applied. Because of the decreased degradation of the insecticide at the lower temperature, the grain could then be held without further cooling.

Aeration of High Moisture Content Grain

Ardrossan, South Australia. It was shown in a trial at Ardrossan, South Australia in 1966 that aeration enabled barley to be stored safely at a higher moisture content than usual (Doolette and Sanders 1966). The trial was conducted in two vertical concrete silos (28.3 m high, 10.7 m diameter, and having a capacity of 1700 t of barley). The silos were filled with barley having average moisture contents of 12 and 14% (wet basis), and aeration was in a downwards direction at a flow rate of 1.0 L/sec/t. It was found that after storage for nine months there were no measurable differences in quality in the barley in both silos. After 1150 hours of aeration the mean grain temperatures were 8°C (in the silo containing 14% moisture content barley) and 10°C (in the silo containing 12% moisture content barley).

Biloela, Queensland. A trial of aeration of grain sorghum of 16% moisture content was carried out at Biloela, near Gladstone in Queensland in 1977 (W.B. Elder, pers. comm.). Two farm silos each of 100 t capacity (3.4 m wall height and 5.8 m diameter) were used. A CSIRO farm aeration unit was connected to a full-round perforated duct (3.0 m long and 0.15 m diameter) positioned along the sloping floor of one silo, and the other silo was left unaerated. The sorghum temperature in the centre of the aerated silo decreased from 31 to 23°C in one month (after about 400 hours of aeration), whereas the unaerated silo centre temperature increased from 31 to 50°C in two weeks as a result of respiration heating. The average sorghum moisture content changed from 15.8 to 15.2% in the aerated silo and from 15.7 to 15.9% in the unaerated silo. The germination percentage changed from 92 to 89% in the aerated bin and to 80% in the unaerated bin. No mould was detected, but the unaerated sorghum had an unpleasant odour on outloading. Aflatoxins were detected in the unaerated bin but not in the aerated bin. This trial showed that grain sorghum can be stored safely for limited periods under aeration while waiting to be dried. This practice is now in commercial use in large aerated silos at Gladstone, before the sorghum is dried in a large tower dryer.

Solar Grain Cooling for the Humid Tropics

In temperate climates, ambient air is often of sufficiently low temperature and enthalpy to provide effective cooling of a grain bulk. However, in tropical climates, which are characterised by hot and humid ambient air conditions, the amount of grain cooling achievable may be inadequate to prevent loss of grain quality. In this case, lower grain temperatures can be achieved by reducing the enthalpy of the ambient air by isothermally lowering its absolute humidity before passing it into the grain bed. This can be carried out in an open-cycle, solar-regenerated, desiccant-bed grain

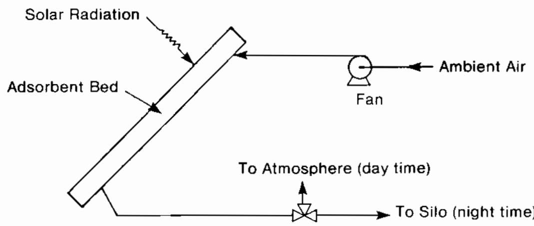

Fig. 14. Schematic arrangement of components in the adsorbent-bed grain cooling system.

cooling system (Thorpe 1981; Thorpe and Fricke, 1985).

The principle of operation of this device, which can be employed in single or multiple stages, is shown in Figure 14. During the night, ambient air is blown through a narrow bed of dry desiccant material so that the heat of sorption can be readily dissipated to atmosphere, and the air of reduced enthalpy is passed into the grain. The desiccant becomes wet, but it is dried during the day by solar radiation falling on the desiccant bed and the simultaneous passage of air through it. During the regeneration process (daytime) the air leaving the adsorbent bed is expelled to atmosphere.

Experiments have shown that by using the solar cooling system, grain temperatures up to 10°C lower than that produced by normal ambient aeration can be achieved (Thorpe 1981). The system is easily built from sheet metal, has no more moving parts than a conventional grain aeration system, can use seed grains as the adsorbent, and ensures drier grain.

Discussion and Conclusions

Trials of a variety of aeration systems using both ambient and refrigerated air have been described. The trials used a mixture of upwards and downwards airflow, and manual and automatic control. In general, upwards flow aeration is now preferred, mainly because the heat of compression added by the aeration fan reduces the relative humidity of the air entering the grain bed. This can remove the need for a humidistat control and restrict the moisture content of the grain near the aeration duct.

When aeration began in Australia, control of fan operation was performed by manual setting of temperature and humidity limits on the ambient air. Also, it was shown by Griffiths (1967) that wet-bulb temperature control was preferable to dry-bulb temperature control, as the temperature reached by the grain is dependent on the air wet-

Fig. 15. Mobile unit for natural aeration of grain.

Fig. 16. Mobile unit for refrigerated aeration of grain.

bulb temperature and the grain moisture content. However, this practice of manual setting of limits made supervision of operation at remote country sites difficult. A number of other controller types, e.g. temperature difference and time switch have been tried, but almost all new aeration systems now installed in Australia use the CSIRO time-proportioning controller (Elder 1972). This controller requires no operator intervention, and automatically selects the coldest periods for aeration fan operation by means of a thermostat which winds down when the fan is running and winds up when the fan is not running. The controller has a rapid setting which ensures operation for 12 hours per day on average and a normal setting which allows 15 hours per week on average. The time-proportioning controller is now commercially available in Australia in both electro-mechanical and electronic forms.

The aeration systems described in this paper have all been fixed. However, mobile grain cooling units are quite possible and a few, using both ambient and refrigerated air, are in use in Australia (Figs 15 and 16). Both the units shown are mounted on trailers and are designed to cool 2000 t of wheat at airflow rates from 1.0 to 1.5 L/sec/t. They use 10 kW centrifugal fans and the mobile refrigerated aeration unit (Fig. 16) has a cooling capacity of 44 kW. The capital costs, in 1980, were about $A2500 for the mobile natural aeration unit and $A15 000 for the mobile refrigerated aeration unit (Hunter 1981).

In general, any degree of grain cooling achieved by aeration is beneficial to the grain, and thus even in the humid tropics aeration can be recommended as a worthwhile method of reducing grain storage problems. In these climates, a technique which would reduce the enthalpy of the ambient air, such as the solar grain cooler described in this paper or some form of dehumidifier, would of course be beneficial.

Acknowledgments

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Paddy Drying in Australia

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Abstract

The rice industry of New South Wales, Australia began in the 1920s as a pioneering venture in the newly established Murrumbidgee River Irrigation Scheme. Early days saw mechanical harvesters stripping the rice at low moisture for bagging, before further drying, storage, and milling. For bag storage, a harvesting moisture limit of 16.5% was imposed. However, because of unfavourable weather, this was difficult to achieve. At the same time, crop size was increasing and 'suncracking' was correlated with rapid drying and wetting in the field. These circumstances eventually led to a change from bag to bulk handling. Since the late 1950s, paddy has been harvested at up to 23% moisture content and dried in deep-bed storage using high-velocity airflows. This strategy dries the paddy to a safe, millable moisture level (13.5%) under controlled conditions and maximises the final grain quality and whole grain yield. Deep-bed drying was well established by the 1970s and research has continued since then on refining the drying process with regard to aeration strategies, energy conservation, grain quality, electronic monitoring and control, pre-heating of air, and automation using minicomputers.

THE growing of rice in New South Wales (NSW), Australia began in the 1920s, thousands of years after neighbouring Asian countries. The impetus to grow rice came from the search for crops that could be grown in the newly created Murrumbidgee River Irrigation Area (MIA) in south-western NSW. However, inexperience, lack of consultant expertise, and inadequate implements resulted in a slow establishment of the industry. It was not until the 1930s that rice growing began to flourish, with annual crops jumping from hundred to tens of thousands of tonnes of paddy. Crop sizes have continued to increase since then (Table 1).

From the beginnings of rice growing in NSW in 1924 until 1956, all paddy was bagged in the field and stored in bags in the rice marketing authority's storage sheds. For satisfactory storage in bags, it was found that the moisture content of the grain should not exceed 16.5%, otherwise there was a danger of mould growth during adverse weather conditions.

In those days, the rice harvest was spread over the months of May, June, and July, when rainy weather is not uncommon, and it was frequently difficult for farmers to reduce the moisture content of the crop to 16.5% in the field. When autoheaders were introduced, the rate of stripping increased and it became more and more difficult to cope economically with the crop in bags.

Bulk handling of wheat had been practiced in Australia for a considerable time, and in 1951 the Rice Marketing Board set about investigating ways and means of handling the rice crop in bulk, as a way of achieving greater efficiency and reducing costs. At about the same time, it became evident that there were other benefits to be obtained if the paddy could be stripped and put into storage at moisture contents up to 23%.

Paddy dried to 16.5% or less in the field, was

Table 1. Growth of the New South Wales rice industry.

Harvest year	Area cropped (ha)	Production (t)	Yield (t/ha)
1925	64	232	3.63
1930	8 093	34 405	4.25
1935	8 847	36 553	4.13
1940	9 819	35 859	3.65
1945	9 953	32 809	3.30
1950	15 006	70 365	4.69
1955	15 651	99 723	6.37
1960	19 783	132 154	6.68
1965	24 894	157 622	6.33
1970	39 033	243 485	6.24
1975	72 316	374 577	5.18
1980	110 257	585 980	5.31
1985	118 300	844 000	6.76

* Ricegrowers' Co-operative Mills Ltd, P.O. Box 561, Leeton, New South Wales 2705, Australia.

subject to cracking. Faults appeared in the kernels of the grain and, during milling, these kernels tended to break more readily, thus reducing the 'mill-out'. This phenomenon is called 'suncracking.'

It was shown that if paddy could be stripped and safely stored at moisture contents up to 23% the incidence of suncracking was greatly reduced, thereby increasing the value of the crop.

In 1956, the Rice Marketing Board converted a bag shed at Leeton to bulk storage with an aeration system consisting of a series of mesh ducts and tubes connected to exhaust fans which drew air through the grain from the top and exhausted the moist air to atmosphere through the axial-flow exhaust fans.

This system demonstrated that, in the climatic conditions of the region, drying with unheated air was effective.

Another experiment was simultaneously carried out at Yenda, near Griffith, in conjunction with the Commonwealth Scientific and Industrial Research Organization (CSIRO) to obtain fundamental data on paddy drying with ambient unheated air. A pilot bin consisting of a radially aerated, cylindrical bin with perforated walls was used.

Both of these experimental grain drying/storage systems were developed to a commercial scale. The radial aeration design was the basis for construction of 60 × 100 t bins (6000 tonnes total) in the Murray Valley rice growing region, to the south of the MIA. Although this was a one-off exercise, these bins are still a functional part of the paddy storage system.

The Leeton 'mesh-duct' pilot plant was a very successful experiment and formed the basis for continuing development. From the experience gained, a rather different system was developed, based on research work carried out at the University of California. This involves blowing air through the grain from the bottom of the bulk, a system which, although simpler from an engineering point of view, proved just as effective. This principle has been maintained, the only changes being in the design of ductwork at floor level. It has proven desirable to have a flat floor. The air is therefore introduced under the floor and passes into the grain through perforated steel sheets flush with the concrete floor of the storage bin.

An alternative to this 'below floor' manifold system is the semi-circular cross section, mesh-covered 'above-floor ducting'. Both air manifolding systems are equally acceptable for aeration, but if the bin or shed is to be used for other purposes, such as storing bagged, milled rice, the semi-circular ducts may be inconvenient and interfere with access by forklift trucks.

It was determined from this early work, that paddy with an initial moisture content of 20–22% could be satisfactorily dried in bulk storage in beds of 5.5–6 m deep by properly controlled, unheated aeration, using an aeration rate of 1 cubic foot per minute per cubic foot of grain.

Considerable supervision of this operation was necessary because the rate of drying depended upon weather conditions.

Growth of the Rice Industry

As the crop size increased through to the 1960s and 1970s, storage capacity also rose, to cope with the drying and storage requirements. The basic design followed the early trial recommendation and is reflected in the 66 horizontal storage sheds dispersed throughout the growing area today.

Paddy was received into storage sheds with little concentration on moisture segregation. Varietal, dockage, and quality segregation took precedence, and the only attempts to segregate on the basis of moisture were to keep aside the very wet paddy and very dry paddy.

As soon as bins were filled, fans were switched on and the aeration program begun. Aeration was controlled by monitoring paddy moisture by sampling at a depth of 1.5 m from the bin surface. Each bin was sampled once per week with 20 samples being taken per 1000 t bin. The results of the tests were then forwarded to Aeration Officers who determined an aeration program for each bin depending on the moisture results obtained.

This program was followed irrespective of the time of year or climatic conditions, except that no aeration was performed during periods of rain or when rain was expected. Paddy delivered for milling at higher than milling moisture content, was dried in the mill hot-air dryers, with single or double pass dependent on moisture. This generally meant that hot-air dryers were used almost continuously for the first few months of each crop year, particularly through the harvest period.

In 1979, based on experiences over immediately preceding harvests, the aeration program was critically examined by technical personnel. This led to the implementation of the following strategy for the 1979 harvest:

• segregation of paddy at receival based on moisture content;

• strict control of moisture testing to ensure at least one series of moisture measurements was completed for each bin each week;

• weekly recording of bin temperatures to enable the overall aeration program to be changed as necessary;

• changes to the aeration program to ensure use of low-speed fans in place of high-speed wherever possible;

• an overriding control of individual bins to enable account to be taken of climatic conditions, paddy needs, and the most cost-efficient drying practices available.

The relatively large size of the 1979 harvest (resulting in 674 000 tonnes) meant that a further complication arose and had to be dealt with. Mills had to be kept running at maximum throughput during harvest to mill as much paddy as possible. This meant minimising double-pass drying at mills which dramatically reduced mill throughput. During the harvest, sufficient paddy had to be dried to below 14.0% to permit safe storage in hired structures with little or no aeration.

These objectives were met during the harvest by performing a large series of half-bin filling and drying operations. By filling the bins to a depth of only 3 m, the resistance to airflow was greatly reduced, resulting in drying of the paddy in approximately one quarter of the time.

Analysis of the performance of the control strategies adopted in the drying of this crop resulted in further changes which were implemented to develop a more efficient aeration program for the 1980 harvest. These were: additional managerial support to control the entire system; upgrading moisture and temperature monitoring to enable more accurate control of drying and storage; and additional managerial aids to store and analyse drying data, so that more accurate aeration programs could be developed for each bin.

The first of these changes was achieved with the appointment of Aeration Supervisors, to liaise with the Co-operative's Technical Services Department in management of drying operations. These supervisors greatly improved the control and efficiency of all drying operations.

After exhaustive evaluation of various devices for remote sensing of moisture, it was decided that no suitable unit was available to monitor moisture in deep beds of grain. The Technical Services Department set about the design and construction of some 7000 sensors based on principles used in other devices. The sensors were completed before the 1980 harvest and were used successfully throughout that and the subsequent harvest.

Apart from construction and installation of a sensor network, a minicomputer was purchased to store and analyse all data collected, and provide an aeration program for each bin, based on contemporary moisture and temperature information.

The minicomputer was programmed to provide an updated aeration program for each bin from daily measurements of moisture and temperature. Receival and transfer data were also fed into the computer to give up-to-date details of bin status. The computer was also used to appraise each bin of paddy in terms of expected whole grain yield. Fans were then switched 'on' or 'off' manually by Aeration Officers according to the aeration program generated by the computer. The computer was programmed with various aeration strategies, the basic objective being to provide dry rice with minimum consumption of electricity.

The following general principles were used in developing this strategy: maximising of aeration in the early period of harvest, making use of the best available climatic conditions; maximising use of half-bin filling; once dry, use of minimum air and, where possible, low-speed fans.

A direct result of the implementation of these strategies was the virtual total abandonment of oil-fired, hot-air column drying and an overall reduction in electricity consumption. These economies were effected despite the fact that rice which was previously dried with column dryers required in-store bin drying and in the face of a 41% increase in the size of the crop. They are illustrated in Figures 1 and 2.

Crop tonnage increases continued to put pressure on the ability to store and dry the paddy. In 1981, a 3000 t rice bin was fitted with LPG gas burners at the aeration fan inlets. Temperature rises of 10°C resulted in marked improvements in drying rates without significantly affecting the whole grain yield, thus greatly increasing the production of dry millable paddy. From the costings it was shown that the additional expense for gas was easily offset by the reduced electricity consumption due to shorter fan running hours. So

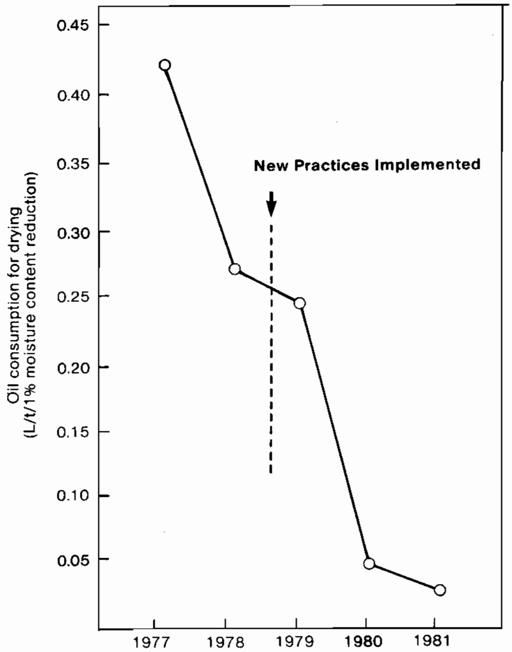

Fig. 1. Reduction in oil consumption for grain drying, following adoption of new practices for drying paddy in Australia.

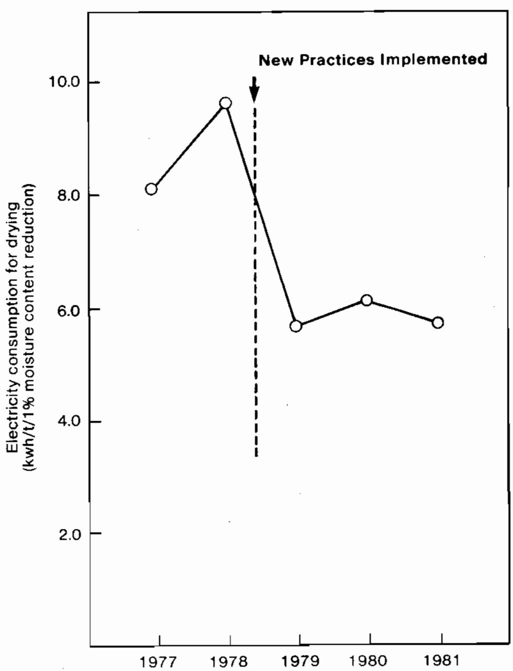

Fig. 2. Reduction in electricity consumption for grain drying, following adoption of new practices for drying paddy in Australia.

successful was this installation that the remaining 3 × 5000 t bins were fitted with burners. An indication of the efficiency of this 18 000 t capacity shed to act as a fast-drying system is shown by the fact that up to 100 000 t of wet paddy now passes through it each year.

In anticipation of a one million tonne crop in 1985, nine additional 12 000 t drying sheds were fitted with LPG gas burners to increase drying capacity early in the harvest and to dry moist paddy in the normally unsuitable wet weather winter.

Fine Tuning of the Drying System

It is our belief that, in terms of horizontal bulk drying and storage of paddy, the past 60 years have seen the development of a highly efficient aeration, drying, and storage system with all areas of major impact having been investigated and refined. Such being the case we have now reached the stage where increases in efficiency will come from fine tuning of the existing strategy by implementing computer-based control and management systems.

In 1981, three 12 000 t paddy storage sheds at the Gogeldrie depot were set up as a first fully automated aeration and drying system.

Individual bins of paddy were continuously monitored for moisture content and temperature, by use of an on-site computer.

In conjunction with the measurement of paddy moisture content, the system also monitored ambient weather conditions and automatically operated the aeration fans on an individual bin basis.

This automatic drying system chose ambient air which gradually dried the grain to an acceptable moisture, as compared with the manual method which can often result in either wetting or overdrying.

The centre of the automatic drying system, the depot control computer receiving information from moisture and temperature sensors in individual bins through the depot, determined the quality of the ambient air for drying purposes and relayed 'on' or 'off' commands to individual aeration fans, as depicted in Figure 3.

Because there were more than 400 separate sensors at the Gogeldrie storage site, it was impossible to individually wire each sensor back to a central location. An advanced communi-

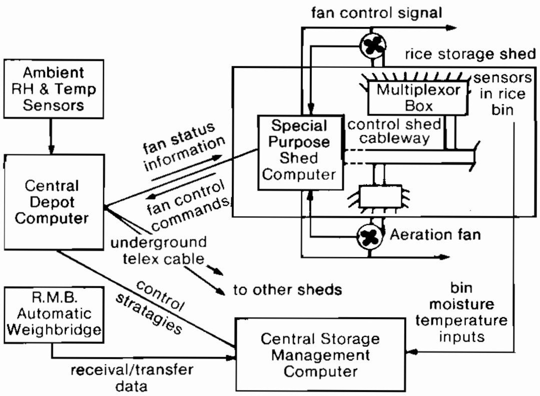

Fig. 3. Ricegrowers' Co-operative Mills' automated aeration system for bulk-stored paddy.

cations scheme was developed to relay sensor readings to the computer.

Each storage shed had been equipped with its own special-purpose shed computer, which acted as a relaying point by gathering bin moisture information in the shed and transmitting this to the central depot control computer via an underground telex line. The special-purpose shed computer also relayed the 'on' or 'off' commands to specific aeration fans in the shed.

The Aeration Supervisor in Leeton was kept informed by daily reports from the depot control computer on the status of grain in individual bins, the hours of fan usage, and other information needed to monitor the quality of stored grain.

As well as controlling grain drying, the depot control computer was linked to the rice marketing authority's automatic weighbridge, and was thereby able to record receivals and despatches of bulk grain at the depot.

This depot was a prototype. After it had operated for two harvests, another depot of similar size was set up using 'off the shelf' electronic hardware. This second automated depot has run very successfully for three harvests and has been used to test many of the aeration strategies from which the current system has evolved.

The State of the Art

The immense amount of work that has gone into the development of the Australian in-store drying system has been aimed at achieving:

- a higher whole grain yield by accepting high moisture paddy into store for controlled drying;
- optimisation of the paddy moisture to a consistent 13.5% by aeration with air selected on a relative humidity/equilibrium relative humidity basis;
- a reduction in fan operating costs by air selection, fan design, and power load shedding;
- a reduction in manpower costs by implementing remote grain and air sensing systems linked to microprocessor controllers and computers.

The most recent step towards achieving even finer control has been in the area of a microprocessor-controlled aeration system with supplemental heating through modulated gas burners. The operation of fans and burners is dependent on the program held within the microprocessor. With inputs from ambient relative humidity and temperature sensors the controller operates fans to achieve the required number of hours at a preset relative humidity. If such air is not available the burners are automatically ignited to reduce relative humidity by raising air temperature by a maximum of 5°C.

The system is new and is still being assessed. However, it is expected to achieve new levels of drying efficiency, while reducing the problems of manual fan switching at remote locations and eliminating concern over the effects of overnight changes in climatic conditions.

In summary, Ricegrowers' Co-operative Mills Limited has been very active in the aeration and drying of paddy rice. Great changes have occurred in the industry as a result of its research and development work, and it is now recognised as a leader in the field of paddy drying technology.

Grain Aeration and In-store Drying in the USA

Do Sup Chung, Boma Kanuyoso, Larry Erickson, and Chong-Ho Lee*

Abstract

Grain aeration is a well accepted practice for maintaining the quality of stored grain. Successful experiences in using aeration systems have been obtained from commercial to farm level in the USA. Of the various drying methods, in-store drying has in recent years been generally accepted at the farm level in the USA.

This paper reviews several studies made of aeration and in-store drying, especially for shelled maize and rough rice, at various locations in the USA. The recommended operating conditions and management methods for grain aeration and in-store drying are discussed, as are the applicability and limitations of aeration and in-store drying methods developed in the USA. In addition, a research project on aeration of rough rice under humid air conditions currently being conducted at Kansas State University is briefly described.

GRAIN aeration is the practice of forcing air through stored grain at low airflow rates to prevent or reduce deterioration of grain quality. The practice of turning grain to equalise temperature and reduce hot spot formation can usually be successfully replaced by aeration. Preventing moisture migration by maintaining a relatively uniform temperature throughout the grain mass, and limiting biological activity by cooling the grain, are probably the most common objectives of grain aeration. Aeration may also reduce the hazard of spontaneous heating when it is necessary to hold moist grain in storage for brief periods. Some storage odours may be removed by air changes during aeration. Grain aeration systems have been used successfully in all principal grain production areas in the United States.

In-store drying can be defined as a process of slow drying with natural air or air heated by only a few degrees (1–6°C). Grain is dried and stored in the same bin. This is also known as deep bed drying and is one method of in-bin drying (Anon. 1980).

In-store drying systems are attractive to grain farmers because of relatively low initial equipment costs, minimum energy input costs, reduced fire hazards, and reduced operational management (Bunn et al. 1981).

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Extensive studies carried out in a number of locations in the USA have provided most of the design criteria utilised in present in-store drying systems. These criteria, however, are based upon local weather and crop conditions.

The objective of this paper is to provide information by reviewing the results obtained from several studies of grain aeration and in-store drying systems, mostly for shelled corn and rough rice at a number of locations in the USA. Recommended operating conditions and management methods for grain aeration and in-store drying are emphasised. The applicability and limitations of the two processes are discussed.

Grain Aeration System: Some Technical Considerations

Aeration may be used to improve the grain storage conditions at either on-farm storage or commercial storage facilities (Calderwood 1975). Although the two types of grain storage are different, the principles of aeration in one type are, in most instances, applicable to the other.

Studies on aeration on flat and deep vertical bins have been discussed by Holman (1960). These studies were originally conducted in cooperation with the agricultural experiment stations of Georgia, Indiana, Iowa, Kansas, Michigan, and Texas.

A study on aeration systems, especially for corn and wheat, in deep bins and flat storages was carried out in Iowa and Indiana by Foster and Stahl (1959). Kline and Converse (1961) carried out an extensive study on grain aeration systems in the hard winter wheat area, with the objective of describing effective methods of using aeration systems to maintain the market quality of grain. Schroeder and Calderwood (1972) discussed the design and operation of aeration systems for rough rice for short-term storage. This study was elaborated for long-term storage by Calderwood et al. (1983).

Proper management of fan operation in grain aeration systems was discussed by Brooker et al. (1974). Foster and Tuite (1982) have focused their discussion on the design and operation of the system.

Table 1. Recommended airflow rates for aerating grains in the United States.

Grain moisture content (%)	Storage type	Airflow rates $m^3/sec/m^3 \times 10^{-3}$	
		Northern States	Southern States
12–15	Farm storage	0.67–1.344	0.67–3.35
	Flat	0.672–1.344	0.896–3.35
	Upright	0.336–0.672	0.448–1.344
15–25	Flat	6.72–10.08	
	Upright	3.36–6.72	

Sources: Holman 1960; Hall 1980; Foster and Tuite 1982.

Types of Aeration Systems

The principal parts of a grain aeration system are: (1) one or more fans to supply the required air; (2) one or more ducts to move air into or out of stored grain; (3) supply pipes to connect the fans and ducts; (4) a motor to operate each fan; (5) a control system to regulate fan operation; and (6) a storage bin in which the grains are stored and aerated.

Holman (1960), and Kline and Converse (1961) pointed out that there are three major types of aeration systems based on combinations of fans and ducts used in the system. These are: (1) a fixed fan system, with a permanently placed fan for each storage bin or for each duct in a storage; (2) a manifold system, with a fan connected to two or more storage bins or ducts through the same manifold; and (3) a portable system, with a portable fan movable from bin to bin or from one part of a storage to another part. Fans and ducts are the two major pieces of equipment needed for the proper delivery of aerating air through the grain mass in terms of the required rate and uniformity of the airflow.

Airflow Requirements

The airflow rate used in grain aeration systems must be adequate to cool all the grains before undesirable changes take place. The airflow rate required depends on the purpose of aeration, the kind of grain, the size and type of storage structure, and climatic conditions (Foster and Tuite 1982).

Compromises are often needed in determining the airflow rate because of limitations on fan power, especially when the resistance to airflow in the system is high.

Table 1 shows the recommended airflow rates for the aeration of stored grain in the USA, as given by Holman (1960), Hall (1980), and Foster and Tuite (1982). The most commonly used airflow rates range from 0.672×10^{-3} to 1.344×10^{-3} $m^3/sec/m^3$ grain. These rates are generally adequate for reducing insect and mould activity and for keeping moisture migration and accumulation within acceptable limits.

Many researchers agree that in most farm-type storages, aeration rates in the range 1.344×10^{-3} to 0.672×10^{-3} $m^3/sec/m^3$ are normally used. An airflow rate of 1.344×10^{-3} $m^3/sec/m^3$ is widely used to aerate shelled corn and soybeans, and for wheat and other smaller seed crops, 0.672×10^{-3} $m^3/sec/m^3$ is more common (Frus 1979; Halderson and Sandvol 1980; Foster and Tuite 1982). Referring to the aeration of dry rough rice in Southern U.S. rice growing region, Calderwood (1975) pointed out that an airflow rate of 1.344×10^{-3} $m^3/sec/m^3$ is generally considered to be adequate.

Static Pressure and Fan Horsepower Requirements

A fan should be selected on the basis of manufacturer's performance ratings. The static pressure, against which the fan must deliver the required airflow, is dependent upon total airflow rate, kind of grain, and grain depth. Fan horsepower requirements are determined on the basis of the total amount of airflow needed and the resistance encountered in forcing the air through the grain. The fan power required increases as the grain depth and the velocity of the air moving through the grain increases. This accounts for the limitation of air delivery through a deep bin.

A convenient method to estimate the static pressure and fan horsepower requirements has been given by Holman (1960) for aerating shelled corn, wheat, rough rice, grain sorghum, oats, and soybeans at different rates of airflow and at depths ranging from 3.05 to 45.72 m. Figures 1 and 2 show the relationship for aeration of shelled corn and rough rice, respectively.

Grain resistance to airflow is obviously essential in designing a grain aeration system. Although many research studies have been made on the resistance to airflow of many kinds of grains and seeds, less attention has been given to providing data on airflow resistance at the low range of airflow rates, which is commonly found in aeration condition. The data reported by Shedd (1953) were based on the minimum airflow rate of 0.0051 m^3/sec/m^3. Also, they were based on a relative clean and dry grain. There are only a few data available on the effects of moisture content and fines and broken contents on airflow resistance (Chung et al. 1984; Chung et al. 1985).

Time Required for Cooling Grain

As aeration progresses, a cooling zone, which moves through the grain in the direction of airflow, is established. The airflow must be adequate to move the cooling zone through all the grain within an allowable time limit. This factor is the most important consideration in establishing time limits for completing a cooling stage.

Holman (1960) pointed out that the time required for cooling a bin of grain to near the outside air temperature depends on the airflow rate, the amount of cooling resulting from evaporation of moisture from the grain during aeration, and the uniformity of the airflow.

A general guide established by Holman (1960) for grain cooling time required in the central part of the United States indicates that cooling time at an airflow rate of 1.344 $\times$ 10^{-3} m^3/sec/m^3 and under favourable conditions is about 80 hours in the summer, 120 hours in the fall, and 160 hours in the winter. The effect of seasonal differences in the amount of evaporative cooling on cooling time has been demonstrated by Foster and Tuite (1982) as seen in Figure 3.

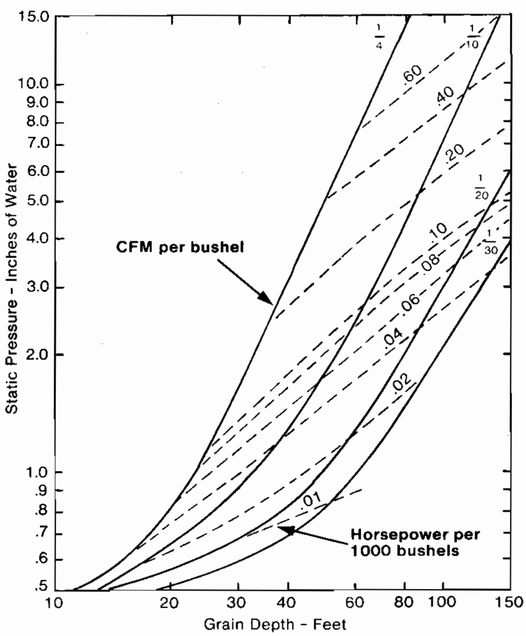


Fig. 1. Fan horsepower and static pressure requirements for aerating shelled maize at various airflow rates and at grain depths ranging from 10–150 feet (Holman 1960). Conversion factors: 1 cfm/bushel = 13.4 $\times$ 10^{-3} m^3/sec/m^3; 1 hp = 745.7 J/sec; 1 inch = 2.54 cm; 1 foot = 0.3048 m; 1 bushel = 0.03524 m^3.

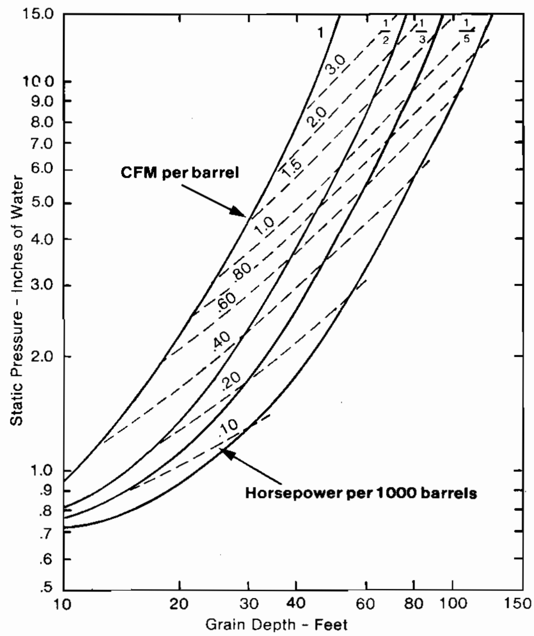


Fig. 2. Fan horsepower and static pressure requirements for aerating rough rice at different airflow rates and at grain depths ranging from 10–150 feet (Holman 1960). Conversion factors: 1 barrel (U.S. dry) = 3.281 bushels = 0.1156 m^3; 1 cfm/bushel = 13.4 $\times$ 10^{-3} m^3/sec/m^3; 1 hp = 745.7 J/sec; 1 inch = 2.54 cm; 1 foot = 0.3048 m.

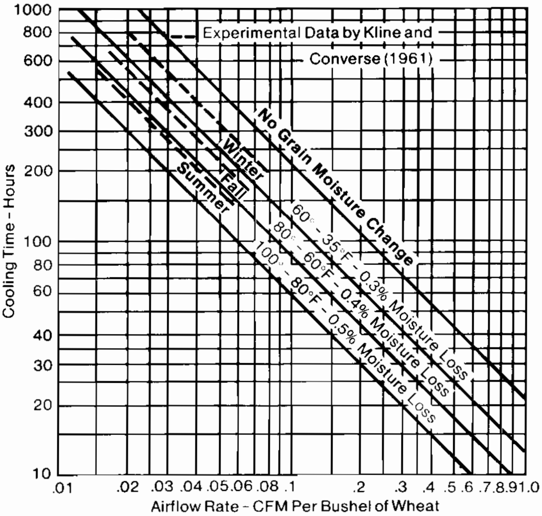


Fig. 3. Effect of airflow rate (cfm = cubic feet/minute) and grain moisture loss on cooling times required (Foster and Tuite 1982). Coversion factors: 1 cfm/bushel = 13.4 $\times$ 10^{-3} $m^3/sec/m^3$; °C = (°F − 32)/1.8.

Table 2. Time required for cooling rough rice, as affected by airflow rates.

Airflow rates ($m^3/sec/m^3$ x 10^{-3})	Time required for cooling (hours)
3.160	17
2.528	21
1.264	42
0.632	84
0.316	168

Source: Schroeder and Calderwood 1972.

Additional data have been produced by Schroeder and Calderwood (1972) showing the time required to cool dry rough rice under Texas weather conditions, as shown in Table 2. An airflow rate as low as 0.376 $\times$ 10^{-3} $m^3/sec/m^3$ was found suitable for cooling dry, rough rice during winter or for equalising temperature during other months.

Recommended Operating Conditions in Grain Aeration

Proper operation of the grain aeration system is essential for maintaining the quality of stored grain. Various conditions and factors must be considered in establishing an effective operation of grain aeration systems.

Grain Moisture Content and Temperature

The condition of grain to be aerated is very important and can determine the success or failure of aerating. Grain can absorb or give up moisture depending on the vapour pressure differential of the air and moisture in grain. When the grain neither loses nor gains moisture, it is in moisture equilibrium with the cooling air.

Holman (1960) determined the maximum moisture content and the corresponding relative humidity for the safe storage of grains, as given in Table 3.

Table 3. Maximum mixture contents for safe storage and corresponding relative humidities for different grains and seeds.

Grain or seed type	Maximum moisture content for safe storage (%, wet basis)	Relative humidity of air at which grain is in equilibrium with air at 25°C (%)
Shelled corn, oats	13.0[a]	61
Wheat (hard red winter)	13.0[a]–13.5	64–68
Wheat (soft red winter)	13.0[a]–13.5	67–73
Wheat (hard red spring)	14.0[b]–14.5	7
Soybeans	11.0	68
Rice	13.0	71
Pea beans	16.0–18.0	76–84
Grain sorghum	13.0	65

Source: Holman 1960.
[a] Southern areas 12%.
[b] Higher moisture limits applicable because of lower average air temperatures in producing areas.

Especially during summer, grain often goes into storage at temperatures of 30°C or higher. Accordingly, grain harvested during summer and fall should be cooled as soon as the atmospheric conditions permit, to avoid deterioration. However, there is no single optimum storage temperature. Storage practices have shown that a grain temperature of 10°C is usually satisfactory, especially if the grain is to be moved during hot weather. If it is not moved, a temperature of 1.5 to 4.5°C is desirable (Holman 1960; Frus 1979).

Atmospheric Conditions

Based on past weather records and results of grain aeration tests that have been carried out, the suggested maximum monthly operating air

Table 4. Suggested maximum monthly operating air temperature for cooling grain in specified areas of the USA.

Month	South East[a]		South West[b]	
	Operating temperature		Operating temperature	
	(°F)	(°C)	(°F)	(°C)
July	85	29.44	90	32.22
August	85	29.44	90	32.22
September	85	29.44	80	26.67
October	70	21.11	70	21.11
November	60	15.56	60	15.56
December	45	7.22	60	15.56
January	45	7.22	50	10.00
February	50	10.00	50	10.00
March	55	12.78	50	10.00
April	60	15.56	60	15.56
May	75	23.89	70	21.11
June	80	26.67	85	29.44

Source: Holman 1960.

[a] Allows aproximately 6 hours of operation each day at relative humidities below 80%.

[b] Allows about 12 or more hours of operation each day under normal conditions.

temperatures for cooling grains were determined by Holman (1960). Data for several areas are presented in Table 4.

It is also a common practice to aerate grain with air having an average relative humidity approximating those values listed in Table 3. However, aeration with air having a relative humidity as high as 80% has proven satisfactory when the air temperature is at least 6°C lower than the grain temperature.

Kline and Converse (1961) suggested that in summer and fall, fans may be operated at all times when the relative humidity is 90% or below and air temperatures are satisfactory. This high limit eliminates fan operation during extended periods of rain and fog. During winter, a maximum relative humidity of 80% is suggested to restrict increase in grain moisture content.

It is interesting to note that if the grain to be stored has a temperature of 35 to 38°C or higher and excess moisture, it may be desirable to run the fan when air humidities are above 80% (Holman 1960). According to McKenzie et al. (1980), the cooling front moves through the grain about 50 times faster than a drying or wetting front. Therefore, only a small fraction of the grain is rewetted during an aeration stage, even with high humidities. Kline and Converse (1961) and Foster (1976) have pointed out that the relative humidity of the incoming air is not critical for the bulk of the grain, since the air is warmed as it passes through the grain and the humidity is reduced.

Direction of Airflow

Aeration can be accomplished by moving the air up or down through the grain. Both downward and upward aeration systems have advantages and disadvantages. In some situations, one system works better, but whether the airflow is upward or downward makes little difference in fan requirements or air delivery (Foster and Tuite 1982).

Two major reasons of moving air down through the grain are as follows: (1) downward movement counteracts the natural tendency of convection currents to move upward to cold surface grain where condensation may occur, and (2) the warm and moist exhaust air is expelled through warm grain in the lower part of the bin. The main disadvantage of moving air downward is the uncertainty of knowing when aeration is complete, since grain at the bottom is the hardest to check.

In the warmer southern area, the use of moving air upwards through the grain has more advantages. The main advantage is that heat trapped under the roof can be forced out at the top, rather than being pulled downward. A more uniform airflow can be obtained by moving the air upward, and aeration progress can be easily determined by checking the grain temperature at the top center. However, especially during very cold and freezing weather, the air moving up through the grain may be cold enough for moisture to condense on the cold grain and on the underside of the bin roof (Holman 1960).

Grain Aeration System Management

System management is a major factor in proper operation of grain aeration systems. From it, comes the decision which will lead to determination of fan operation schedules (Foster and Tuite 1982).

Problems in Operation

Experience has shown that the methods of operating grain aeration systems often vary from one area to another, due to the different climatic conditions. Further, the purpose of aeration is not always the same.

In northern states, where there is a wide difference in winter and summer temperatures, the prevention of moisture change during storage is probably the most important use of aeration. In the more humid southern areas of the United States, the problem of maintaining grain with moisture content near the upper limit for safe storage is the major concern, besides the problem of insect control. In these areas, aeration is used to keep the grain as cool as practical in order to stop moulding, heating, and other deterioration processes.

Larger capacity aeration systems are used to speed the cooling during the limited amount of favourable cooling weather in the south (Foster and Stahl 1959).

Another precaution should be taken when dealing with summer-harvested grains, particularly wheat and oats, which require a different operational schedule to corn and other grains harvested in the fall. It is often necessary to remove the harvest heat from wheat and oats quickly to avoid damage from heating and insects.

Operation Schedules

To successfully aerate stored grain for long-term storage, it is necessary to calculate the number of days required to cool a bin of grain and total aeration time per year for a lot of stored grain. The number of days required depends on the percentage of each day that is suitable for aeration, and in estimating total aeration time per year, the number of cooling stages involved should be considered.

Ordinarily, grain is cooled by aerating it by successive stages during the summer, fall, and winter. There is a possibility of cooling grain in either a single stage or two stages, by postponing a certain part of the aeration process until later in the season when the air temperature is low enough to cool the grain to the desired temperature. One objection to this last method, especially cooling in a single stage, is that aeration may be so late that some grain has deteriorated or moisture migration has occurred. Typical cooling of grain in three stages is illustrated in Figure 4.

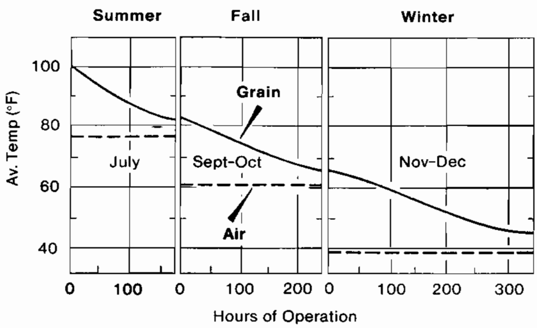


Fig. 4. Aeration of wheat by stages at an airflow rate of 0.672 × 10^{-3} $m^3/sec/m^3$ (Holman 1960). Conversion factor: °C = (°F − 32)/1.8.

Foster and Tuite (1982) described the aeration schedule for the corn belt area in the United States as follows: (1) the grain should be aerated as soon as possible to reduce the temperature to 15–21°C for summer-harvested grain and to 10–15°C for fall-harvested grain. Summer-harvested grain normally needs to be aerated again in the early fall to reduce the temperature to 10–15°C; (2) the grain is then aerated in the late fall to cool it to between −1 and 4°C; no further aeration is recommended until spring, unless storage problems develop; (3) in March or April, grain may be aerated to warm it to 10–15°C.

The schedule outlined above was based on daily 24 hours fan operation where appropriate conditions exist. If the average relative humidity remains high for several days, the fan should not be operated except when the relative humidity is below 70–80%. Intermittent aeration can be scheduled according to forecast weather information. A control system, which is usually a combination of thermostats and a humidistat, is required for such an aeration system.

Experiments conducted by Calderwood et al. (1983) indicate that in the Texas rice area, the weather conditions are such that 100 hours or more of aeration system operating time can be expected each month from November through March using a thermostat set for fan operation at temperatures of 15°C or lower in series with a humidistat set for fan operation at relative humidites of 70% or lower.

Recommendations for Operating Grain Aeration System

Some specific recommendations for successful aeration in the midwestern USA as described by Brooker et al. (1974) and summarised by Bakker-Arkema et al. (1978) are as follows: (1) operate the aeration fan for a few days immediately following the initial storage of the grain; (2) operate the fan only when the ambient temperature is 6–8°C below the grain temperature and the relative humidity of the air is below 70%; (3) cool the grain to between 2 and 10°C depending on the length of storage; (4) operate the fan for several hours a week; and (5) warm the grain to 21°C in the spring by reversing the process used in the fall.

Applicability of Grain Aeration in the Humid Tropics

In warm, humid, tropical areas, where the conditions are mostly favourable for the growth and activities of microorganisms and insects, a major portion of the grain postharvest losses is still due to the inadequate facilities and improper ways of handling, drying, and storing grain materials. The prevailing atmospheric conditions in these areas are characterised by relatively high temperatures ranging from 21 to 35°C, and humidities averaging 75–80% or higher.

It is obvious that cooling by aeration to reduce the temperature to less than 18–21°C is unlikely to be achieved, because cold air is not available.

Storage structures are normally not insulated, and seasonal and diurnal climatic changes of air temperature and solar radiation therefore cause the outer portions of the grain mass to gain or lose heat and change temperature. Moisture migration may occur as a result of non-uniform temperatures within the stored mass of grain. The practice of aeration is needed in particular to equalise the grain temperature during storage. It should be carried out in conjunction with other preservation treatments, such as fumigation.

As the relative humidity increases to higher than 75%, the use of moving air through the grain should be very carefully managed, as some moisture is likely to be adsorbed from the air. Depending on local weather conditions, there may be possibilities for aerating stored grain on occasional days or for a few hours on each of a number of days when aeration will be effective. Information on this topic is still very limited and more research is needed.

Aerating Rough Rice under Warm, Humid Conditions

A research project on aeration of rough rice under warm, humid conditions is being conducted at Kansas State University. The primary objective is to investigate the extent of heat and mass transfer occurring during aeration of dry rough rice in a storage column, under conditions which may represent the typical atmospheric conditions in humid tropical areas. Experiments are conducted with clean, dry, long grain rough rice and with the conditions as follows:

Initial moisture content	13.0–14.5%
Initial grain temperature	29.44–35°C
Aerating air temperature	21.11–29.44°C
Aerating air relative humidity	70–90%
Aerating airflow rates	1.344×10^{-3}–5.376×10^{-3} m³/sec/m³

The tests are made with the insulated grain column inside a controlled environmental chamber where both temperature and relative humidity are maintained at the desired level. The conditioned air is blown upward through the grain by a fan equipped with a variable speed motor. The temperatures and moisture contents of the grains during aeration are measured at certain positions along the bed column and at certain time intervals, until a cooling stage is completed.

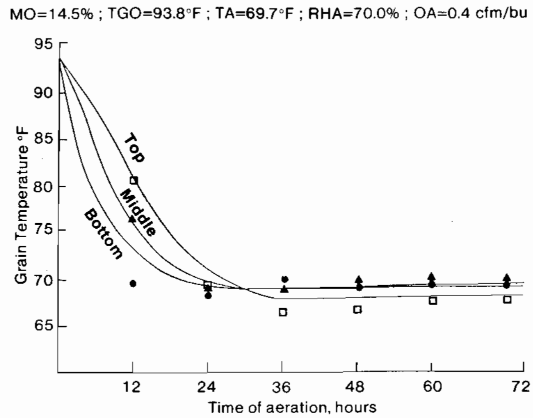


Fig. 5. Grain temperature versus time of aeration through rough rice. Conversion factors: 1 inch = 2.54 cm; °C = (°F − 32)/1.8; 1 cfm/bushel = 13.4×10^{-3} m³/sec/m³.

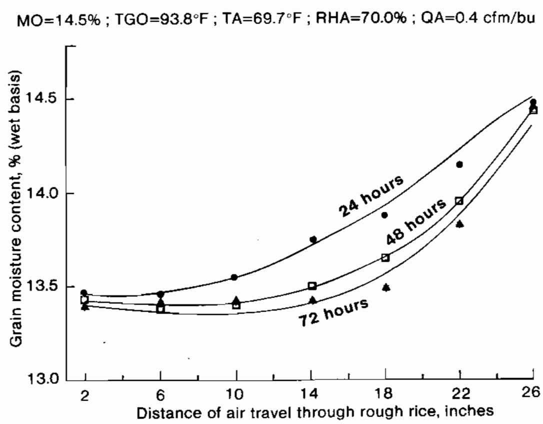


Fig. 6. Grain moisture content versus distance of air travel through rough rice during aeration. Conversion factors: 1 inch = 2.54 cm; °C = (°F − 32)/1.8; 1 cfm/bushel = 13.4×10^{-3} m³/sec/m³.

Experimental work is still underway. Some preliminary experiments have been conducted and the data obtained are presented in Figures 5 to 8. Figures 5 and 6 show the changes in grain temperatures and moisture content, respectively, under the following aeration conditions: (1) initial grain moisture content, 14.5%; (2) initial grain temperature, 93.8°F (34.3°C); (3) aerating air temperature, 69.7°F (20.9°C); (4) aerating air relative humidity 70%; and (5) aerating airflow rate 0.4 cfm/bu (5.376×10^{-7} m³/sec/m³). From Figure 5, it can be found that rough rice temperature decreases to temperatures lower than the average aerating temperature of 69.7°F

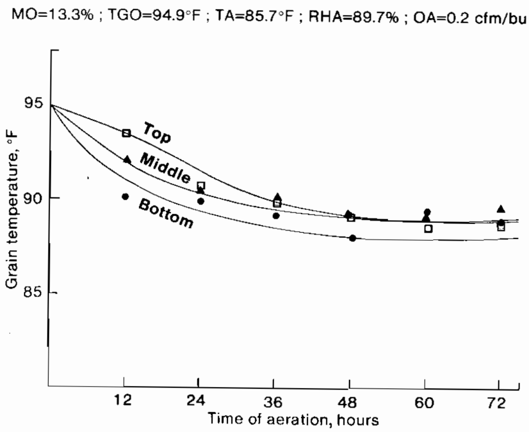


Fig. 7. Grain temperature versus time of aeration for rough rice. Conversion factors: 1 inch = 2.54 cm; °C = (°F − 32)/1.8; 1 cfm/bushel = 13.4×10^{-3} m³/sec/m³.

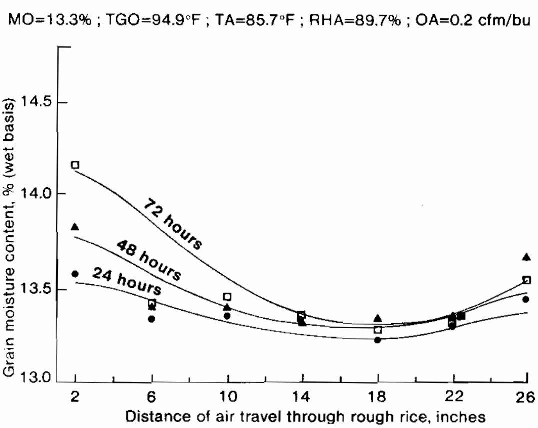


Fig. 8. Grain moisture content versus distance of air travel through rough rice. Conversion factors: 1 inch = 2.54 cm; °C = (°F − 32)/1.8; 1 cfm/bushel = 13.4×10^{-3} m³/sec/m³.

(20.9°C), indicating that evaporative cooling of the grain has taken place during the aeration. This might be explained by considering that the aerating air temperature is 24.1°F (13.4°C) lower than initial grain temperature, so that the vapour pressure differential between moisture in grain and vapour in air is strong enough to cause moisture transfer from the grain to the air. This is also in agreement with the decrease in moisture content, especially in the lower part of the grain bed as shown in Figure 6. Figure 5 also shows that cooling time for this aeration is about 27 hours, which is higher than the values given by Holman (1960) and Schroeder and Calderwood (1972). A better comparison could be made if aeration conditions for these other studies were known in detail.

Figures 7 and 8 show the grain temperature and moisture content changes as affected by aeration under the following conditions: (1) initial grain moisture content, 13.32%; (2) initial grain temperatures, 94.9°F (34.9°C); (3) aerating air temperature, 85.7°F (29.8°C); (4) aerating air relative humidity, 89.7%; and (5) aerating airflow rate 0.2 cfm/bu (2.688×10^{-3} m³/sec/m³). From Figure 7, it can be observed that grain temperature decreases to around 88.5°F (29.8°C). The relative humidity of the aerating air is relatively high, and aerating air temperature is less than 10°F (5.6°C) lower. Adsorption is therefore more likely to occur than desorption. This is in agreement with the increase of moisture content of the grain during aeration particularly in the lower part of the rough rice column. From Figure 7, cooling time is found to be about 48 hours, which is generally in agreement with cooling time reported previously. After 48 hours cooling, the increase in average grain moisture content is about 0.16%, which can be considered small.

In-store Drying Systems: General Technical Background

Although in-store drying has been known and used for a considerable time since the 1950s, experience shows that the technique has not always been well adapted. As already pointed out, these systems are attractive to grain farmers; however, by using ambient air or slightly heated ambient air for the drying medium, slower rates of drying will generally be associated with the systems. This will increase the risk for grain spoilage. The potential for spoilage, in many instances, outweighs all other economic considerations (Saul and Lind 1958; Steele et al. 1969; Thompson 1972). Ambient air conditions play a major role in determining the effectiveness of in-store drying systems.

The design, management, and performance of in-store drying systems have been treated in general in a number of publications from the United States Department of Agriculture (USDA), state agricultural experiment stations, and industry. Research and experience by these groups have yielded reliable design data for most of the features of such systems. Among the most important guidelines are the recommendations given by USDA (1965) on maximum grain depth and minimum airflows for natural air drying in the USA, as shown in Table 5.

Important information on the principles of in-store drying, which is also known as low temperature drying, and recommended practices for the North Central region have been presented, giving emphasis on the system for shelled corn (Anon. 1980). Foster (1953) conducted tests to determine the airflow rates required for drying wheat and shelled corn with unheated air under Indiana weather conditions. Tests to determine the practicability of drying rough rice in storage bins at Beaumont, Texas, were made by Morrison (1954). The results obtained indicate that rough rice can be dried using unheated air under weather conditions in the Texas rice belt.

Henderson (1955) conducted studies to determine the optimum air rate for deep bed, unheated-air rice dryers for California installations, to determine the effect of various performance features upon final rice quality, and to attempt to apply the findings to other rice producing areas. He concluded that deep bed, unheated air rice dryers would produce good quality rice in California if the proper airflow rate through the mass was applied.

Sorenson and Crane (1960) made tests at Beaumont, Texas, during seven crop years (1952–53 through 1958–59) to determine the practicability of drying rough rice in-store in Texas. The results obtained emphasised the importance of time-temperature-initial moisture relationship in reducing the moisture content of rice to below 15%.

Table 5. USDA recommended maximum grain depths and minimum air flows for natural air drying[a].

Type of grain	Grain moisture content (%)	Recommended depth of grain (feet)	(m)	Recommended minimum airflow (cfm/bu)	($m^3/sec/m^3 \times 10^{-3}$)
Wheat	20	8	2.44	3	40.3
	18	10	3.05	2	26.9
	16	12	3.66	1	13.4
Oats	25	8	2.44	3	40.3
	20	11	3.35	2	26.9
	18	12	3.66	1.5	20.2
	16	16	4.88	1	13.4
Shelled corn	25	6.5	1.98	5	67.2
	20	10	3.05	3	40.3
	18	12	3.66	2	26.9
	16	16	4.88	1	13.4
Grain sorghum	20	8	2.44	3	40.3
	18	10.5	3.20	2	26.9
	16	16	4.88	1	13.4
Rice	22	6	1.83	4	53.8
	20	8	2.44	3	40.3
	18	8	2.44	2	26.9
Barley	20	8	2.44	3	40.3
	18	10	3.05	2	26.9
	16	14	3.14	1	13.4
Soybeans	20	10	3.05	3	40.3
	18	12	3.66	2	26.9
	16	16	4.88	1	13.4

Source: USDA 1965.
[a] These are somewhat conservative. No location specified.

Since the advent of computer technology, a number of researchers have attempted to simulate the in-store drying of grain. Several models have been proposed to describe the heat and mass transfer processes in the in-store grain drying systems. It appears that computer simulation offers the greatest potential for predicting performance of the system.

An in-store drying system generally consists of a bin for both drying and storing grain, a fan and motor to force the air through the product, and an appropriate air distribution system. The air distribution systems commonly used are a perforated floor or various arrangements of ducts and laterals. Hall (1980) has pointed out that the success of in-store drying systems depends on proper selection and design of component parts, proper management of the systems, and desirable atmospheric conditions.

Allowable Storage Time

In-store drying is an effort to get the grain dried before it spoils. The key is to move the drying zone up and through the top of the grain within the allowable storage time. To select an airflow rate for a natural air drying system, information on allowable storage time is necessary.

Mould is the major cause of spoilage in grain. By controlling moisture content and temperature, mould growth is restricted and grain can be dried without significant spoilage. Grain temperature and moisture determine the allowable storage time

Table 6. Allowable storage time for shelled corn[a]. (Developed from Thompson, transaction of ASAE 333–337, 1972.)

Grain temp. deg. F	Corn moisture, percent						
	18	20	22	24	26	28	30
				days			
30	648	321	190	127	94	74	61
35	432	214	126	85	62	49	40
40	288	142	84	56	41	32	27
45	192	95	56	37	27	21	18
50	128	63	37	25	18	14	12
55	85	42	25	16	12	9	8
60	56	28	17	11	8	7	5
65	42	21	13	8	6	5	4
70	31	16	9	6	5	4	3
75	23	12	7	5	4	3	2
80	17	9	5	4	3	2	2

Source: Anon. 1980; Hellevang 1983. Developed from Thompson 1972.

[a] Conversion factor: °C = (°F − 32))/1.8

(AST) for corn which shows how long grain can be kept before it spoils, as shown in Table 6. This table shows the allowable storage time for corn, which is the time until 0.5% dry matter decomposition is reached. The data show that as moisture content or temperature increases, the allowable time for drying and storing decreases. This means that wetter or warmer grain requires higher airflow rates in order for drying to be accomplished within the allowable time (Hellevang 1983).

Airflow through Grain

Airflow is the major factor affecting the performance of in-store drying systems. Airflow rates largely determine drying time. In the USA, these airflow rates are measured in cubic feet per minute per bushel (cfm/bu), where 1 cfm/bu is equal to 0.01344 $m^3/sec/m^3$. From previous experiments conducted by comparing the progress of the drying front in the bins, which differ only in the way they are equipped and their energy requirements, it was found that the more air is delivered, the faster the drying front moves through the grain, the greater the amount of water removed, and the more reliable the system is. However, there are practical limits to how much airflow can be delivered to a full bin because the grain acts as a barrier. This airflow resistance is largely influenced by airflow rates, grain depth, and kind of grain. Grain cleanliness and the amount of packing are other influencing factors (Anon. 1980).

Sorenson and Crane (1960) recommended an airflow rate 12.9×10^{-3} $m^3/sec/m^3$ for rough rice having an initial moisture content of 25% wet basis. With this airflow rate, the rice bed usually should be no deeper than 2.44 to 3.01 m (8 to 10 ft) for economical use of power. In the California rice-growing area where the climate is drier and cooler than in the Texas rice-growing area, Henderson (1958) recommended airflow rates of 5.7×10^{-3} $m^3/sec/m^3$ and 9.2×10^{-3} $m^3/sec/m^3$, respectively, for rough rice having initial moisture contents of 20 and 25%.

Resistance to airflow is obviously fundamental in the design of in-store drying systems. Many research studies of resistance to airflow have been done on the measurement of pressure drop in a deep bin at various depths of grain and airflow rates. The work of Shedd (1953) resulted in the availability of important data relating pressure drop with airflow rate and grain depth for many kinds of grains and other seeds, as shown in Figure

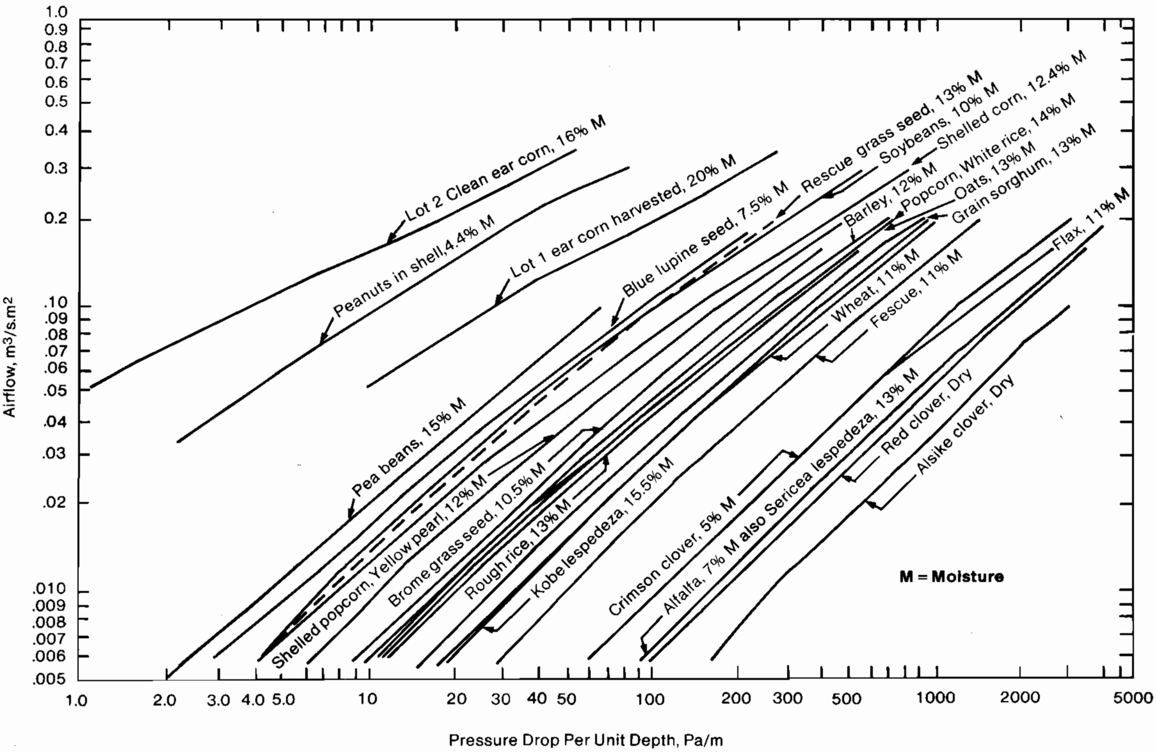
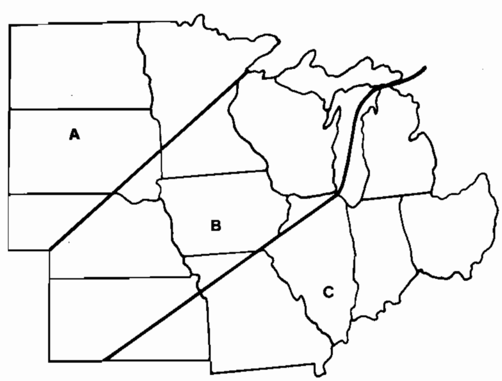


Fig. 9. Resistance of grains and seeds to airflow (ASAE 1982).

9. However, direct application of Shedd's data is limited to loose-filled, clean, relatively dry grain and seeds. Several attempts have been made to improve their applicability by investigating the effects of other important variables, such as moisture content, amount of broken and fine materials, and amount of packing. Chung et al. (1984) developed an empirical equation relating grain moisture and fines to static pressure of grain sorghum at flow rates ranging from 0.075 to 0.19 $m^3/sec/m^3$. They concluded that static pressure drop in grain sorghum increased with a decrease in moisture content and increased with an increase in fines and broken material. Chung et al. (1985) investigated the effects of moisture content and foreign material in rough rice on airflow resistance. The model developed, within a airflow rate range of 0.0508 to 0.304 $m^3/sec/m^3$, has the same form as that for grain sorghum developed by Chung et al. (1984). They concluded that increasing moisture content decreased the pressure drop, and increasing the foreign material also decreased the pressure drop.

In selecting a fan for a new system, Figure 10 shows the recommended full-bin airflow rate applicable in the North Central region of the United States. The eastern and southern portions of the region need higher airflows because of higher humidities and somewhat warmer temperatures at harvest. A higher airflow than the minimum in Figure 10 increases drying speed, gives an added



A Provide at least 13.4 x 10^{-3} $m^3/sec/m^3$ (1 cfm/bu)
B Provide at least 16.8 x 10^{-3} $m^3/sec/m^3$ (1.25 cfm/bu)
C Provide at least 20.2 x 10^{-3} $m^3/sec/m^3$ (1.5 cfm/bu)

Fig. 10. Recommendations of full-bin airflow rates for fan selection (Anon. 1980).

Table 7. Static pressures required for shelled corn[a].

Grain depth feet	0.5	0.75	1.0	1.25	1.5	1.75	2.0	2.25	2.5	2.75	3.0
	Airflow rate cubic feet per minute per bushel										
	static pressure, inches of water										
2							0.1	0.1	0.1	0.1	0.1
3			0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2
4		0.1	0.1		0.2	0.2	0.2	0.3	0.3	0.4	0.4
5	0.1	0.1	0.2	0.2	0.3	0.3	0.4	0.5	0.5	0.6	0.7
6	0.1	0.2	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
7	0.2	0.2	0.3	0.5	0.6	0.7	0.9	1.0	1.2	1.3	1.5
8	0.2	0.3	0.5	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.1
9	0.3	0.4	0.6	0.8	1.0	1.3	1.6	1.8	2.1	2.4	2.8
10	0.3	0.5	0.8	1.0	1.3	1.7	2.0	2.4	2.8	3.2	3.6
11	0.4	0.7	1.0	1.3	1.7	2.1	2.5	3.0	3.5	4.0	4.6
12	0.5	0.8	1.2	1.6	2.1	2.6	3.1	3.7	4.3	5.0	5.7
13	0.6	1.0	1.4	1.9	2.5	3.1	3.8	4.5	5.3	6.1	7.0
14	0.7	1.2	1.7	2.3	3.0	3.7	4.6	5.4	6.4	7.4	8.4
15	0.8	1.4	2.0	2.7	3.5	4.4	5.4	6.5	7.6	8.8	
16	0.9	1.6	2.3	3.2	4.2	5.2	6.4	7.6	8.9		
17	1.1	1.8	2.7	3.7	4.8	6.1	7.4	8.9			
18	1.2	2.1	3.1	4.3	5.6	7.0	8.5				
19	1.4	2.4	3.5	4.9	6.4	8.0	9.8				
20	1.5	2.7	4.0	5.5	7.2	9.1					

Axial fans: above solid line. Centrifugal fans: below dashed line.

Source: Anon. 1980.
[a] Avoid static pressure above 5.0 inches of H_2O.
Conversion factors: 1 inch = 25.4 mm; 1 foot = 0.3048 m; 1 cfm/bu = 13.4×10^{-3} $m^3/sec/m^3$.

margin of safety, and reduces the need to finish drying in spring.

Table 7 shows the static pressure required for shelled corn for various airflows and grain depths. This table can be used as a guide to determine the maximum practical airflows. A system for less than 11.4 cm H_2O static pressure is preferable to reduce drying cost (Anon. 1980). Recommendations for designing an in-store drying system were given as follows (Anon. 1980); (1) bin is equipped with full perforated floor; (2) a grain distributor is installed; (3) a minimum of airflow rate at 1 cfm/bu (0.0134 $m^3/sec/m^3$) is provided; (4) roof opening is of 1 sq ft/1000 cfm (0.055 m^2/1000 m^3/hr); (5) static pressure is designed at 11.4 cm H_2O or less; and (6) bin depth is limited to 20 feet (6.1 m), 14 feet (4.3 m) is preferred.

Managing an In-store Dryer

To handle harvest moisture conditions for a given year, three filling strategies have been suggested: (1) Single filling, when the bin is filled in 1 to 3 days; (2) layer filling, when the grain is added in layers over a period of time; and (3) controlled filling, when layer filling is managed in a specific way (Anon. 1980).

Zone	Full-bin airflow $m^3/sec/m^3$ $\times 10^{-3}$	9-1	9-15	10-1	10-15	11-1	11-15	12-1
		Harvest date						
		Initial moisture content, percent						
A	13.4	18	19.5	21	22	24	20	18
	40.3	22	22.5	24	25.5	27	22	18
B	13.4	19	20	20	21	23	20	18
	40.3	21	22.5	23.5	24.5	26	22	18
C	13.4	19	19.5	20	21	22	20	18
	40.3	21	22	23.5	24.5	25.5	22	18
D	13.4	19	19.5	20	21	22	20	18
	40.3	20.5	21.5	23	24	25	22	18

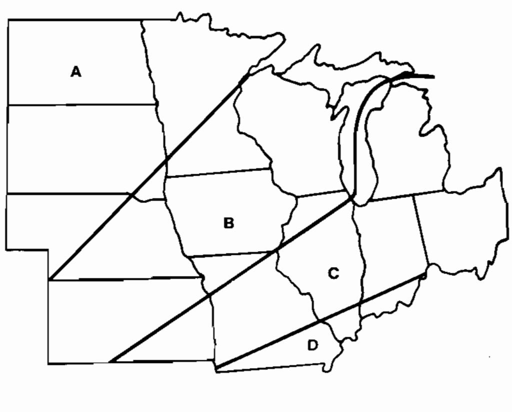


Fig. 11. Maximum maize moisture contents for single-fill drying. Developed by T.L. Thompson. (Anon. 1980).

For single filling systems, harvest moisture content is the limiting management factor. It is more suitable for varieties known for early field dry down. Figure 11 gives the maximum initial moisture content for single filling systems, depending on harvest date and airflow rate.

Layer fillings usually involve the first grain, which is also the wettest. Limiting grain depth to get a higher airflow rate is one way to handle this higher moisture grain, which in this case is corn.

Controlled filling is similar to layer filling except the drying front does not come through the top before another layer is added.

Sorenson and Crane (1960) recommended the following operating schedule for unheated air drying in Texas: (1) start the fan as soon as the air distribution system is completely covered; (2) operate the fan continuously as the bin is filled and until the moisture content of rough rice at 0.3 m (1 ft) below the top surface is reduced to 15%; (3) operate the fan then only when the relative humidity of ambient air is 75% or less; and (4) continue drying until the moisture content of rough rice 0.3 m (1 ft) below the top surface is reduced to 12.5%.

Regardless of filling strategy, common management practices for in-store drying systems can also be described as follows: (1) the best drying procedure is to operate fans continuously until the drying front has moved through the top of the grain. The fan is not shut off in the fall during periods of rainy weather or high relative humidity. The fan can be shut off when the drying front has moved through the top of the grain or when all the grain has been cooled to about -3.9°C; (2) the crop can be held over winter with above normal storage moisture content by cooling it with aeration and with weekly observation. Check any changes in moisture content or increase in grain temperature. Run the drying fan a total of six to eight hours about every two weeks when the outdoor temperature is between -6.7 and -1.1°C. Cover the fan after it has been shut off to avoid flowing air currents; (3) drying can normally be safely completed in the spring if needed. About a month is required, so that allowable storage time should be checked for spring conditions (Hellevang 1983).

A study made by Morey et al. (1979) leads to the conclusions that, based on the management procedures studied, continuous fan operation under appropriate fall shut-off and spring start-up procedure is preferable for management strategies.

Supplemental Heat

Addition of supplemental heat to the air reduces grain moisture content in the lower layers of the bin, but does not reduce moisture content in the top of the bin. By controlling the addition of supplemental heat, the desired final moisture content may be more easily achieved and rewetting during an extended period of damp, cold weather, can also be prevented.

If average moisture content is to be lowered by the end of fall, increasing airflow is preferable to addition of supplemental heat, since additional airflow has more advantages in terms of reliability and drying capacity.

For an unstirred, low temperature dryer, a solar collector can provide adequate supplemental heat because: (1) the longer drying period provides an extended period for collecting solar energy, (2) night and short periods of cloudy weather seldom cause problems because grain stores energy; and (3) higher airflow requirements along with low temperature rises mean that collectors can be used (Anon. 1980). Calderwood (1979) made a study of rice drying with solar heat by collecting the heat in the daytime, storing it in a suitable medium such as a rock-bed or solar pond, then using it at night or at other times when relative humidity is high. It was concluded from this study that time for drying and hours for fan operation were lower with solar heat than with unheated air, and milling yields of rice samples dried with either solar heated air or unheated air were equivalent.

Simulation Studies

A simulation study of natural air drying of rough rice has been conducted at Kansas State University by Chang et al. (1978). A series of simulated drying tests using official weather data for 15 years from Beaumont, Texas were taken and fan models were developed to determine minimum airflow rate and maximum bed depth of rough rice drying by natural air.

During the actual experiments conducted, a fan was operated continuously until the moisture content of the top layer of grain reached 15%. It was then operated only when relative humidity was 65% and lower. Since only Steele's data for corn storage were available as far as the dry matter loss equation is concerned, the success or failure of a given simulation was determined using two criteria: (1) allowable storage time is based on a criterion of 0.5% dry matter loss (Steele et al. 1969); and (2) in unheated air and supplemental heat drying application under Texas conditions, the moisture in the wettest layer of rice was to be reduced below 15% in 15 days or less to prevent loss in grade from discoloured kernel (Sorenson and Crane 1960). Using the fan model developed, economic airflow rate and bed depths can be recommended. For initial moisture contents 24, 22, 20, and 18% wet basis, minimum airflow rates are 0.067, 0.040, 0.027, and 0.013 $m^3/sec/m^3$, respectively, and maximum bed depths are 0.91, 1.52, 2.13, and 2.44 m. These results were similar to the USDA recommendations, as described by Sorenson and Crane (1960). From this study it is obvious that well defined and acceptable grain deterioration criteria for each kind of grain should be determined to ensure success of future simulation studies.

In a preliminary study of rough rice drying in a tropical country, Chang et al. (1978) simulated grain drying for two harvesting seasons using Costa Rica weather data (Fig. 12). In this simulation, airflow rate was 0.040 $m^3/sec/m^3$, bed depth was 1.524 m, initial moisture content was 27.0%, and initial air temperature was 26.67°C. Rough rice was dried from 20 May–28 June 1976. Final dry matter loss of top layer was 0.437%. This preliminary finding may show the possible application of rough rice drying by natural air under tropical weather conditions.

A mathematical model has also been used by Chang et al. (1979) in developing a simple dryer selection model for on-farm drying facilities to optimise costs for the drying systems.

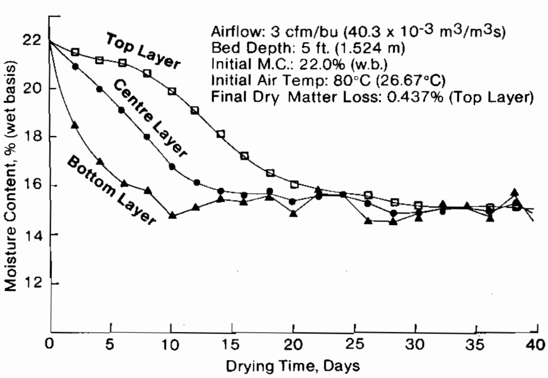


Fig. 12. Moisture content and drying time of each layer of rough rice dried under Costa Rican weather conditions, starting on 20 May 1978 (Chang et al. 1978).

Acknowledgment

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Case Studies on Aeration and In-store Drying Session Chairman's Summary

Dante B. de Padua*

THE papers in this session described the small and large grain drying and storage systems existing in the Asian region; their success as well as their problems in operation.

Mr Loo Kau Fa described the different types of facilities found in the LPN complexes in Malaysia. They consist basically of continuous flow bulk handling, cleaning and drying facilities, and bulk storage of either the horizontal bin or vertical silo type. The operational problems described include poor performance of cleaners and scalpers with extremely wet and dirty grain, yellowing of grain in vertical silos, and insect infestation. Control measures undertaken include turning of grain from one silo to another, aeration, and chemical fumigation. An airflow rate of 0.1 m^3 per tonne of grain per minute, in a system where air is introduced at the bottom of silo, was found to be the most cost effective in controlling yellowing of the grain.

The paper of Mr Calverley, presented by Mr Boxall, dwelt on the concept of an in-store drying facility installed with BULOG in Indonesia and the results obtained after a long struggle. While the results do indicate feasibility of in-store drying, TDRI admits that such a system would have serious limitations and difficulties in solving BULOG's problems.

Mr Justin Tumambing provided the background of the drying problem in the Philippines, the state of the art of existing technologies, some basic grain moisture equilibrium studies, and initial results of pilot plant trials in two-stage drying. It was noted that the EMC of some varieties tested had a higher ERH at 14% m.c. than published values of other varieties.

Dr Somchart Soponronrarit reviewed the post-harvest practices in Thailand, and discussed an integrated drying and storage system using solar huts at the farm level.

Dr Hong-Sik Cheigh discussed a system for small farm drying and storage of paddy in South Korea, which was designed to match the capacity according to cultivation, and used natural ventilation or mechanical aeration.

The system with a capacity of 2-4 tons of paddy has found wide acceptance in Korea, with over 10 000 units installed.

Mr Sutherland discussed the case studies involving 13 trials of aerating grains in Australia. Seven of these trials were on natural aeration in large stores and two on aeration of high moisture content grain. The trials indicated that aeration is beneficial for controlling grain insect populations, eliminating temperature gradients, reducing moisture migration, slowing down pesticide degradation, and preserving grain quality. The cost of aeration system was also found comparable with the costs of insecticide treatment. Aeration was recommended as a worthwhile method of reducing grain storage problems even in the humid tropics. Under humid tropical conditions, the use of a dehumidifier or an open cycle solar-regenerated desiccant-bed grain cooling system was recommended to reduce the enthalpy of ambient air.

Mr Bramall described circumstances leading to the development of a drying system for rice in Australia. The shift from bag to bulk handling prompted developmental works on drying at high velocity airflows in deep-bed storage. This method is continuously being refined with emphasis on aeration, energy conservation, grain quality maintenance, electronic monitoring and control, preheating of air, and automation using minicomputer.

Dr Chung discussed grain aeration and in-store drying in the USA. In-store drying is generally accepted and practiced at the farm level in the USA. He cited various studies on aeration and in-

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store drying. He recommended management methods under various operating conditions for grain aeration and in-store drying. Also, the limitations and application of the method were discussed. He further noted that a research project on aeration of rough rice under humid air conditions is being conducted at Kansas State University.

For the humid tropics, the consensus was to evolve a two-stage drying system, where the high moisture harvest is rapidly dried down to more manageable levels. The final drying may be done in storage, but it was recognised that the latter required a greater degree of supervision compared with the high temperature, high airflow, continuous-flow dryers favoured in the US.

There was a high degree of cost consciousness associated with the different options, and that cost/benefit analysis should be an integral part of the decision-making process.

Concluding Session

Summary of Seminar

B. R. Champ*

In my summary of the seminar proceedings, I do not propose to reiterate what our chairmen have so capably said. Rather, I would like to highlight one or two especially relevant issues that I feel have emerged.

It is evident to me from listening to the various papers that the seminar has been opportune in coinciding with times of major change in approaches to preserving grain quality by physical methods, such as aeration and in-store drying.

Very importantly, the *systems approach* to aeration and drying is now being fully recognised. The technologies are not being considered in isolation as in the past when facilities were developed and their performance dictated quality and the handling and storage systems that could be used. As our understanding of the basic technology has increased, we are now more able to purpose design our aeration and drying capacity to meet the needs of the industry and to interpose it into a total system that ensures that the quality of the grain as produced is preserved through to final consumption.

This leads of course to the intrusion of *economics* into the drying and aeration fields. Engineers and biologists have come to realise that they also can no longer work in isolation, and they are now working side by side with economists. The benefits are immense. The technology so developed is viable and justifiable, and hence has a better chance of introduction into the industry to the benefit of all. I trust we all agree that the cooperative approach between technologists and economists is now mandatory in all our activities.

A problem that has to be faced increasingly today is that resources for loss reduction and related research activities are limited — and by limited, I mean that the total resources available are less than those in aggregate that are required to fully address the problem. Economic assessments can be made of proposed interventions at different points where losses of commodity occur in the chain from production to final disposal. These assessments will provide an objective comparison of the potential benefits to be derived, so that priorities can be established to maximise the return from the resources available.

A critical element in all these developments has been the advances in *computer technology*. The fast, high-capacity units that are now readily available in compact form at affordable prices have revolutionised the whole area of aeration and drying technology and the integral economic considerations. Simulation modelling can now reach its full potential in taking into account all the parameters that are relevant, whether it be in determining the location and size of dryers on a regional basis, or the detail of movement of moisture through grain during drying. It is no longer necessary to make assumptions and all variables can be taken into account as, for example, came out in the discussions on the different theories of drying where equilibrium need not be assumed.

The other exciting development is of course in process control whereby manual operations can be replaced by microprocessor control with its attendant precision. The level of competence in supervision of an operation is thus that of the designer of the software not of an unskilled field worker.

Let me now move to some specific points. We have heard considerable discussion on theoretical aspects of aeration and drying. But we have also heard reference to problems in the quality of the

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grain that is to be preserved, and how quickly quality is lost after treatment.

The inclusion of trash with grain presented for drying is a major constraint to effective implementation of the technology. Obviously, pricing and procurement policies must be revised to help overcome this problem. Similarly, the point has been made repeatedly that the present pricing arrangements encourage farmers *not* to dry grain, and this is happening in that critical period immediately after harvest when the grain is very prone to quality deterioration. We must accept that proper drying commences from the moment of harvesting or even before then, and that this must be taken into account in design of the procurement systems.

In this context, the point was made that there is need for models to be developed to quantitatively define quality. These are needed to realise the full potential of optimisation models used in assessment of the various processes integrated into postharvest handling of grain. I believe the need for these has been recognised and that appropriate descriptors are on the way.

Reference was also made to the influence of varietal characteristics of grain on loss of moisture during drying. We therefore need to approach plant breeders to investigate the possibility of breeding new rice varieties, varieties, for example, with different water activity characteristics that permit easier drying in the humid tropics.

The problems of using aeration and in-store drying in the humid tropics are soluble. Attention has been, and will continue to be, given to providing an adequate research base for the technology, and developing from this, handling and drying systems that are compatible with the requirements of the region. It seems most probable that use of aeration and in-store drying will happen and will expand in the region. We must ensure that the benefits that will accrue from their introduction are not delayed and are maximised by ensuring that the difficult problems of transposing research to commercial practice are addressed and overcome expeditiously.

On behalf of ACIAR and GASGA, I would like to express our appreciation of the efforts of our local colleagues in LPN, MARDI, and AFHB whose hard work, carried out in a thoroughly professional manner, has made this seminar possible and successful.

I would also like to express the thanks of the organisers to the speakers, the chairpersons, and rapporteurs and to all participants for invaluable contributions.

Closing Remarks

J.P. Mercader*

I am honoured to deliver these closing remarks for the seminar on Preserving Grain Quality by Aeration and In-store Drying. Dr Fredericks, the Director of the Bureau, tenders his apologies for not being able to be here in view of urgent official commitments.

In closing this seminar, I am obliged to look back at the discussions over the past three days. To a very large extent, I believe that the seminar has achieved its objectives, namely reviewing the current state of the art of in-store drying and aeration, assessing in both technical and economic terms the relevance of these technologies to the handling of wet paddy in the humid tropics. The 24 papers presented and the discussions they stimulated were sufficient to attain these objectives and bring about a greater awareness of the problems and opportunities in overcoming problems related to drying and aeration.

In retrospect, the seminar has affirmed some critical points and insights on the subject. These are:

(1) That drying is an integral part of the postharvest system and is interrelated with other processes in the system. In attempting to solve problems related to drying and aeration, there appears a need to consider and integrate them with other aspects such as harvesting and handling, storage, milling, and marketing and distribution.

(2) The seminar also confirmed to a large extent that the engineering aspects of drying technology have reached a stage of near-perfection and the problems related to drying are peripheral to the technology, but are nevertheless critical factors for consideration if losses in drying are to be minimised.
These are problems which hinge on paddy quality standards and price structures, policies related to marketing, and the provision of incentives for viable participation by the private sector in the postharvest handling chain. In this regard, the seminar directly and indirectly calls for policy review and redirection.

(3) The seminar is also a vivid demonstration of interest and support in solving the problems related to drying of grains under humid tropical conditions. I note with gratitude that studies on drying under humid tropical conditions are being conducted even in temperate countries. These efforts are comforting and should be encouraged. This is the very nucleus for meaningful development cooperation. As these efforts appear to be directed at solving problems in the humid tropics, they would be more meaningful if they go beyond the technological sphere of the problem and consider ancillary factors that influence the adoption of the technology. These factors appear to be the greater bulk of the problem, at least in this region.

It is encouraging to note that the seminar was actively participated in by delegates from notable research, education and development institutions from all over the world and most especially from the private sector.

In closing, I would like to think that the seminar has stirred greater interest for further research works, development efforts, and review and reformulation of policies related to maintaining grains quality. Thank you.

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