

Figure 4. The predicted pressure distribution in an aerated hopper bottomed circular grain silo.

Acknowledgments

The author is grateful to the Grains Research and Development Corporation for providing financial support for this work, and to the Australian Centre for International Agricultural Research for providing funds to enable the author to present this paper at the

Conference on Grain Drying in Asia. The author expresses his gratitude to Associate Professor I. D. G. Mackie, Head, Department of Civil and Building Engineering, for providing a supportive research environment.

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Nomenclature

$f_j(x,y)...$	Descriptors of the physical boundaries of the grain store.
t	Time, s.
T	Temperature, K.
$\eta, J_{mx}, J_{my}...$	Coefficients in equations 6.
u	Horizontal component of velocity, m/s.
v	Vertical component of velocity, m/s.
x,y	Coordinates in the physical domain, m.

Greek symbols

$\alpha_1, \alpha_2, \alpha_3, \alpha_4$	Coefficients in the transformation equations 3 and 4.
$\beta_1, \beta_2, \beta_3...$	Coefficients in the transformed laplacian, equation 5.
ξ, η	Coordinates of the computational domain.

An Evaluation of the Returns to Research on Grain Drying and Storage in the Philippines

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POSTHARVEST losses and wastage in grains in the humid tropics are attributed to several factors, such as weather, climate, and inadequate drying and storage facilities. In the Philippines in recent years about 60% of paddy and 72% of maize are harvested during the wet season, July–December (BAS 1994). Harvested grain is not dried properly, especially during the wet season, resulting in high moisture contents: 26–28% for paddy and 36% for maize (Tumaming 1984). When high moisture grains are stored at high temperature and humidity the results are dry matter reduction and weight loss, quality deterioration, and grain damage. Insect infestation exacerbates postharvest losses. These losses increase marketing costs, and contribute to a drain on the country's buffer stock of rice.

In addressing the problem of postharvest losses, the National Postharvest Institute for Research and Extension (NAPHIRE) in the Philippines and the Australian Centre for International Agricultural Research (ACIAR) have conducted closely interrelated research on alternative grain drying and storage in the Philippines. The results of those projects suggest a potential for reducing postharvest losses of grains in the Philippines.

This paper aims to present an alternative analytical framework for evaluating the economic impacts of research on grain drying and storage. That framework is used to measure the economic impact of a series of ACIAR-supported research projects on two-stage grain drying (NAPHIRE n.d.), storage of grain using

plastic covers, and pesticide use (NAPHIRE n.d.) (Table 1).

An Alternative Economic Framework for Evaluating Research on Postharvest Losses

Research evaluation methods have evolved from the subjective checklist and scoring models, to more objective methods such as production function, linear programming, and economic surplus. The application of more objective methods is part of an international trend to subject agricultural research to more careful economic evaluation in an effort to use research resources more efficiently (Mangabat 1995).

The economic surplus approach, which uses the concepts of producer and consumer surpluses, has now been widely used as a framework in measuring changes in economic welfare from research. Consumer surplus is the maximum amount that consumers are prepared to pay over what they actually pay for a given quantity of a commodity. Analogously, producer surplus refers, in general, to the excess of what producers receive for supplying a given quantity over the minimum amount that they would need in order to willingly supply that quantity (Hertford and Schmitz 1977). This section of the paper presents a postharvest waste reduction model developed by Davis (1994) that is based on the economic surplus approach. This model is adapted to evaluate a series of ACIAR–NAPHIRE collaborative research projects on alternative grain drying and storage in the Philippines. The postharvest wastage research model is an extension of research on multistage production systems (Freebairn et al. 1982; Alston and Scobie 1983).

The effects of research that reduces postharvest wastage are illustrated graphically in Figure 1. The

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lines in the II and IV quadrants represent wastage transformation lines from the farm to retail store (a 45° line gives the case of zero wastage). The postharvest services sector (transport, drying, handling) is assumed to have a perfectly elastic supply, implying that the cost of the activities in this sector represents only a small share of the total cost of the agricultural commodity activity.

Fixed proportions are assumed, implying that postharvest services are used in the same proportion as the farm product for whatever price and quantity. With the use of existing postharvest technology (without research) wastage is assumed to be, say, 40%. The supply curves are S_f (farm sector), S_m (postharvest sector), and S_r (retail sector). The demand for postharvest services is a derived demand from the retail sector. A new postharvest technology reduces wastage of the farm product to 35%. If the new technology increases postharvest costs, the postharvest supply curve shifts to S_m' . The wastage reduction and cost effect due to retail supply curve to shift to S_r' . The new equilibrium conditions are lower retail price (P_r'); increased grain consumption (Q_r'); decreased farm output (Q_f') due to a slight fall in farm price; and a change in postharvest services (an increase in this case).

The welfare effects of research are measured as the areas suggested in Figure 1. Consumers (CS) gain by the area $P_r'xyP_r'$; gains to producers depend upon the change in resource cost, and the supply and demand

elasticities. Producer gains increase as demand becomes more elastic and supply becomes more inelastic.

Alternatively, prices and quantity changes are used to measure research welfare effects. Following Davis and Lubulwa (1994), supply and demand equations characterising market equilibrium conditions in without and with research are specified as follows:

Without research

Farm level supply [Fig. 1 (III)]
 $Q_f^S = a + b P_f$ (1)

Farm to retail production linkage [Fig. 1 (III)]
 $Q_r^S = c + Q_f^S$ (2)

Farm to retail price linkage [Fig. 1 (IV)]
 $P_f = cP_r - M$ (3)

Retail sector supply [Fig. 1 (I)]
 $Q_r^S = c[a + b (cP_r - M)]$ (4)

Retail demand [Fig. 1 (I)]
 $Q_r^D = d - gP_r$ (5)

Retail market equilibrium [Fig. 1 (I)]
 $Q_r^S = Q_r^D$ (6)

where P_f and P_r are farm and retail prices; a , c , and d are the intercept terms; b and g are the supply and demand slopes, where $b = ef Q_f/P_f$, $g = nr Q_r/P_r$, where e_f is price elasticity of supply at farm level, nr is the price elasticity of demand at retail; c is farm to

Table 1. ACIAR–NAPHIRE collaborative postharvest research projects for evaluation.

Category/ Project no.	Project description	Commodities	Research type
<i>Grain drying</i>			
8308	Drying in bulk storage	Paddy	Wastage reduction
8608	Development of a two-stage drying system	Paddy, maize, peanuts	Wastage reduction, quality change
9008	Application of in-store drying	Paddy	Wastage reduction, quality change, cost change
<i>Use of plastic cover storage</i>			
8307	Application of plastic covers for grain storage	Paddy	Wastage reduction
8845	Design of an outdoor storage to complement indoor storage	Paddy, maize	Wastage reduction
<i>Pesticide use in grain storage</i>			
8309	Development of effective pest control treatments in storage of high moisture grains	Maize, mungbeans	Wastage reduction
8609	Complete the development of effective pesticide treatments	Paddy, maize, mungbeans	Health effects, cost change
9009	Minimising pesticide residues in grain using mixtures of protectants and concentrates	Maize, mungbeans	Health effects, cost change

retail level conversion factor. The wastage rate of a commodity from farm to retail level is $(1 - c)$ where $0 < c < 1$. For example, if wastage rate is 30%, then $c = 0.7$. Equations (1) to (6) can be solved for the without research conditions.

With research

Reduction in postharvest wastage:

$$c' = (c + c) \tag{7}$$

Change in postharvest input costs:

$$M' = (M + M) \tag{8}$$

where the superscript (') denotes the with research conditions. Equations (7) and (8) can be substituted into equations (1) to (6) to solve for the with research equilibrium prices and quantities, $P_f, P_r, Q_f,$ and Q_r and to measure changes in total surplus (TS) and its distribution to producers (PS) and consumers (CS). The algebraic expressions in measuring the benefits to research are :

$$CS = (P_r - P_r') Q_r + 0.5[(P_r - P_r')(Q_r - Q_r')] \tag{9}$$

$$PS = (P_f' - P_f) Q_f + 0.5[(P_f' - P_f)(Q_f' - Q_f)] \tag{10}$$

$$TS = CS + PS \tag{11}$$

Evaluation of ACIAR-NAPHIRE Research Projects

Some of the ACIAR-supported postharvest research projects have previously been evaluated using standard financial and economic analyses: costs of projects compared with benefits, and allocation of benefits between ACIAR and NAPHIRE (see Chudleigh 1991; Ryland 1991).

Related research projects under each category are evaluated based on their collective effect. For example, the research impact of grain drying projects

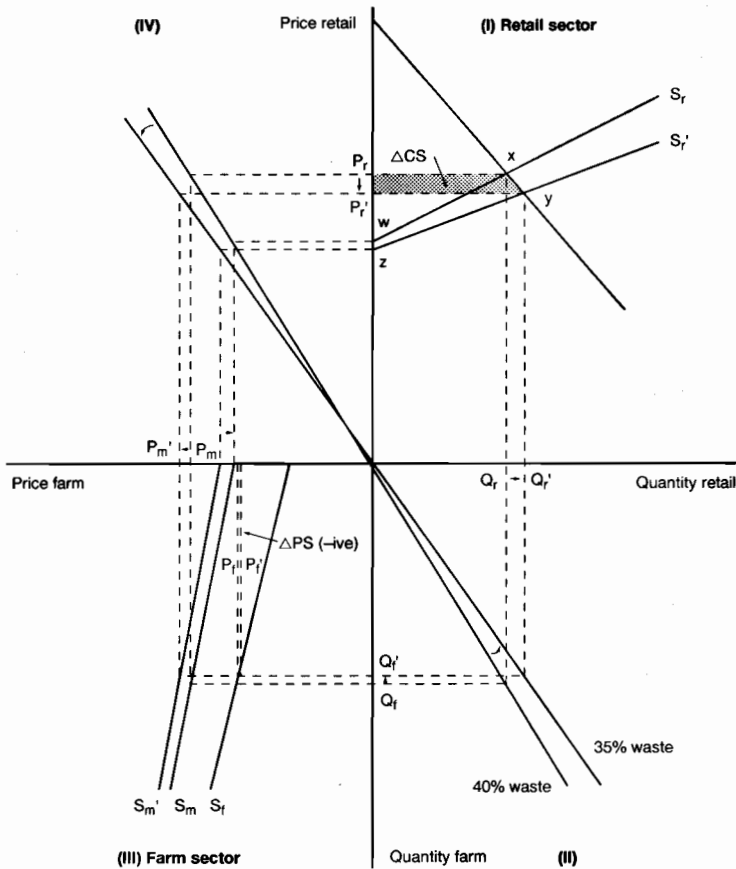


Figure 1. Postharvest wastage reduction model.

(ACIAR PN8308, 8608, and 9008) will be on changes in wastage reduction and cost of paddy drying. There are other assumptions adopted in the present research evaluation. An ex-ante research assessment is used because the dissemination of the postharvest technologies is at an early stage. The wastage reduction and cost effects introduce a parallel shift of the farm supply curve implying a uniform rate of technology adoption and equal cost reduction across all producers. The analysis is partial equilibrium, focusing on a specific grain industry. Measurement of research gains is annual static, interpreted as gains accruing in a year. Adoption of improved technologies and adjustments in supply and demand occur within the year. Research costs are not included, so the estimated research gains represent gross benefits.

Table 2. Parameter values for postharvest research evaluation.

Parameter	Description	Values
<i>Marketable quantity^a</i>		
Q _f	Paddy	4,345,198 t
	Maize	3,550,503 t
Q _r	Rice	3,490,180 t
Q _w	Maize	3,550,503 t
<i>Farm price</i>		
P _f	Paddy	\$236.4/t
	Maize	\$188/t
P _r	Rice	\$532/t
P _w	Maize	\$214/t
<i>Price elasticity of supply</i>		
e _f	Rice	0.40, 0.62
	Maize	0.42, 1.03
<i>Price elasticity of demand</i>		
n	Rice	-0.523 3/, 0.8
	Maize	-0.63 4/, 0.8
<i>Wastage reduction</i>		
c	Paddy	0.75 5/, 0.8
	Maize	0.75, 0.8
<i>Cost reduction</i>		
M	Paddy	\$5/t
	Maize	\$10/t

^a Quantities sold and landlord share (BAS 1994). On average, marketable quantity from total production is 15% for paddy and 74% for maize.

Sources: Estrada and Bantilan (1991); Tumaming (1995).

The values and definitions of the parameters used in the present research evaluation are provided in Table 2. A sensitivity test is conducted for price elasticities of supply (e) and demand (n), percent change in wastage reduction, and postharvest cost.

Results

The values of the yearly gross benefits resulting from research are shown in Table 3.

Table 3. Size and distribution of Philippine benefits from research on grain drying and storage (in US\$ per year).

	e	0.40	0.62	
	n	-0.528, -0.4,	-0.528, -0.8	
	c' = 0.75, m' = \$5/t			
<i>Grain drying</i>				
PS	481.3	(137.9)	20.3	297.4
CS	(134.7)	364.8	162.2	(138.4)
TS	346.6	226.9	182.5	159.0
	c' = 0.08, m' = \$10/t			
PS			39.3	
CS			143.2	
TS			182.5	
<i>Plastic storage (without M')</i>				
PS	467.5		5.0	284.3
CS	(145.3)		150.0	(147.9)
TS	322.2		155.0	136.4
	c' = 0.8			
PS			5.1	
CS			115.0	
TS			120.1	
<i>Use of pesticide</i>				
e	0.42		1.03	
n	0.63		-0.63	-0.8
	c' = M' = \$5/t			
PS	170.1		(154.8)	257.0
CS	(51.5)		246.4	(163.5)
TS	118.6		91.6	93.5
	c' = 0.8, m' = \$10/t			
PS	178.2			
CS	167.72			
TS	110.5			

The costs of research are not included, as the individual research projects under each category (grain drying storage and use of pesticide) are evaluated collectively. Benefits to research range from US\$110.5 (use of pesticide) to US\$346.6M (grain drying). The size and distribution of aggregate benefits are sensitive to the assumptions of the price elasticities of supply and demand, and the size of wastage reduction and change in postharvest costs.

From the baseline data for paddy and maize ($e = 40$, $n = -0.528$; $e = 0.42$, $n = -0.63$, respectively), aggregate benefits are larger the less elastic is the supply of the commodity compared to its demand. Research that reduces wastage in postharvest activities and at the same time induces a decrease in postharvest costs, results in greater benefits than when research reduces wastage alone. The latter assumes that the costs of postharvest activities in the without and with research conditions are the same.

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Preservation of Grain with Aeration

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Abstract

Aeration involves moving relatively low volumes of air through bulk stored grains for the purpose of controlling grain temperature. Grain temperature is the primary stored grain management tool to minimise the risk of fungal spoilage and insect damage. The primary objective of aeration is to maintain temperatures in grain as uniformly as possible, and as low as practical. Grain moisture is the second critical grain management factor. Generally, aeration airflow rates are too small to dry grain. However, excessive aeration can reduce marketable grain weight. Grains with harvest moisture contents above the safe storage limits must first be dried with forced heated or natural air. Under certain climatic conditions and in various geographic locations, aeration with ambient air cannot completely inhibit insect activity and preserve grain quality. When grain temperatures cannot be sufficiently reduced, aeration with chilled air is a technically feasible alternative for grain temperature management. Chilled grain aeration, in contrast to ambient aeration, cools grain independently of the ambient temperature and humidity. To be effective, aeration has to be part of an overall preventive postharvest management system involving sanitation, loading, aeration and monitoring (S.L.A.M.) of bulk stored grains. In addition to a review of grain aeration principles, the effectiveness of preserving grain quality utilising both ambient and chilled aeration is presented for Thai, Brazilian and U.S. conditions using both maize and paddy rice.

Aeration is the forced movement of ambient air through stored grain to decrease or increase the grain temperature to the desired level. Although ambient airflow rates are generally too low to significantly change grain moistures by more than 0.5 percentage points, excessive aeration can reduce marketable grain weight, or cause swelling of grain kernels near the air inlet. The approximate fan run times for a range of common airflow rates are listed in Table 1. The recommended U.S. design airflow rate for aeration is $0.1 \text{ m}^3/\text{min}/\text{t}$. In warm, humid regions airflows of at least $0.125\text{--}0.25 \text{ m}^3/\text{min}/\text{t}$ should be considered to minimise fan run times and maximise utilisation of cooler weather.

Grain temperature is the major stored-grain management tool that regulates insects and moulds (Noyes et al. 1995). Harvest temperatures vary widely for grain and seed crops across the world. In temperate latitudes, grain is generally harvested later and can be stored at higher moisture levels than in tropical latitudes. For example, the maize harvest in the southern U.S. typically occurs from mid-July through September at moisture contents (m.c.) of 12–18% wet basis (w.b.), but in the northern U.S. harvest is usually in October and November at moistures of 18–25% (w.b.). Thus, producers and elevator operators in the north can cool grain much sooner after harvest than those in the South, who generally do not have to dry artificially. Most insect and mould activity is greatly reduced at grain temperatures below 15°C . Planned temperature reductions with controlled aeration can significantly reduce insect development.

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Grain moisture is the other critical grain management factor that regulates storability. Higher levels of grain moisture increase the potential for both insect infestations and mould development, although moisture content is more critical in its formation. To achieve safe storage moisture contents, forced heated or natural air drying of crops is necessary, especially for maize harvested in the midwestern U.S., rice in Southeast Asia, and wheat in the Canadian prairies. At times, soybeans, sorghum, oats, rye, and other grains may also need to be dried after harvest. Table 2 summarises safe grain storage moisture levels for southern, central, and northern regions of the U.S. Grain is at higher risk in warmer, humid regions than in temperate, drier regions due to higher temperatures and relative humidities between harvest and aeration cooling. Thus, lowering storage moistures by at least 1–3 percentage points of those listed for the southern U.S. are recommended for warmer and more humid regions outside the USA.

Table 1. Airflow rate and approximate fan run times (hours) for aeration of grain in different seasons to equalise grain temperature (from Brooker et al. 1992).

Season	Airflow rate (m ³ /min/t)		
	0.05	0.1	0.25
Fall	300	150	60
Winter	400	200	80
Spring	240	120	48

Stored grain insect populations and mould growth accelerate rapidly under extended favourable growing conditions. As illustrated in Figure 1, if temperature and grain moisture levels are favourable, stored grain insects and moulds will increase exponentially. Stored grain managers must be aware of the increase in risk, based on the time the product has been stored at grain temperatures and moisture levels suitable for development. The predicted effects of two grain moistures and temperatures on insect levels in wheat harvested 1 June in the central plains of the U.S. but not aerated before 1 October closely model field experience (Hagstrum and Flinn 1990). On the other hand, if aeration was started earlier, insect development could be controlled below the critical 1 live insect per 0.5 kg limit (Fig. 2).

As grain is dried slowly and/or aerated, its moisture content comes into equilibrium with the surrounding (interstitial) air temperature and relative humidity of the drying or storage environment. Figures 3–6 illustrate moisture equilibrium conditions for several common grain types, based on published ASAE Standards (Anon. 1992). If air temperature increases at a constant relative humidity, the grain's

equilibrium moisture content (EMC) will decrease. If relative humidity increases at constant temperature, EMC will increase. As shown in Figure 3, maize stored at 15% m.c. (w.b.) and 10°C has an equilibrium relative humidity of about 68%. If, due to excessive aeration, the interstitial relative humidity was measured to be 60% at 10°C, the grain moisture level would have been reduced to about 13.5% w.b. Thus, knowing the relationship between EMC and air conditions is important in properly managing aeration systems to prevent overdrying or condensation.

Table 2. Maximum moisture contents recommended for aerated grain storage across the U.S. (from Noyes et al. 1995).

Grain type and storage time	Maximum moisture content ^a for safe storage (% wet basis)		
	South	Central	North
Shelled maize and sorghum			
Stored up to 6 months	14	15	15
Stored 6 to 12 months	13	14	14
Stored more than 1 year	12	13	13
Soybeans			
Stored up to 6 months	13	14	14
Stored 6 to 12 months	12	12	13
Stored more than 1 year	11	11	12
Wheat, oats, barley, rice			
Stored up to 6 months	12	13	14
Stored 6 to 12 months	11	12	13
Stored more than 1 year	10	11	12
Sunflower			
Stored up to 6 months	10	10	10
Stored 6 to 12 months	9	9	9
Stored more than 1 year	8	8	8
Flaxseed			
Stored up to 6 months	9	9	9
Stored more than 6 months	7	7	7
Edible beans			
Stored up to 6 months	14	15	15
Stored 6 to 12 months	12	13	14
Stored more than 1 year	10	11	12

^a Values for good quality, clean grain and aerated storage. Reduce one percentage point for poor quality grain, such as grain damaged by blight, drought, etc. Reduce each entry by two percentage points for non-aerated storage. Reduce the values for the Southern U.S. by one to three percentage points for warm, humid regions.

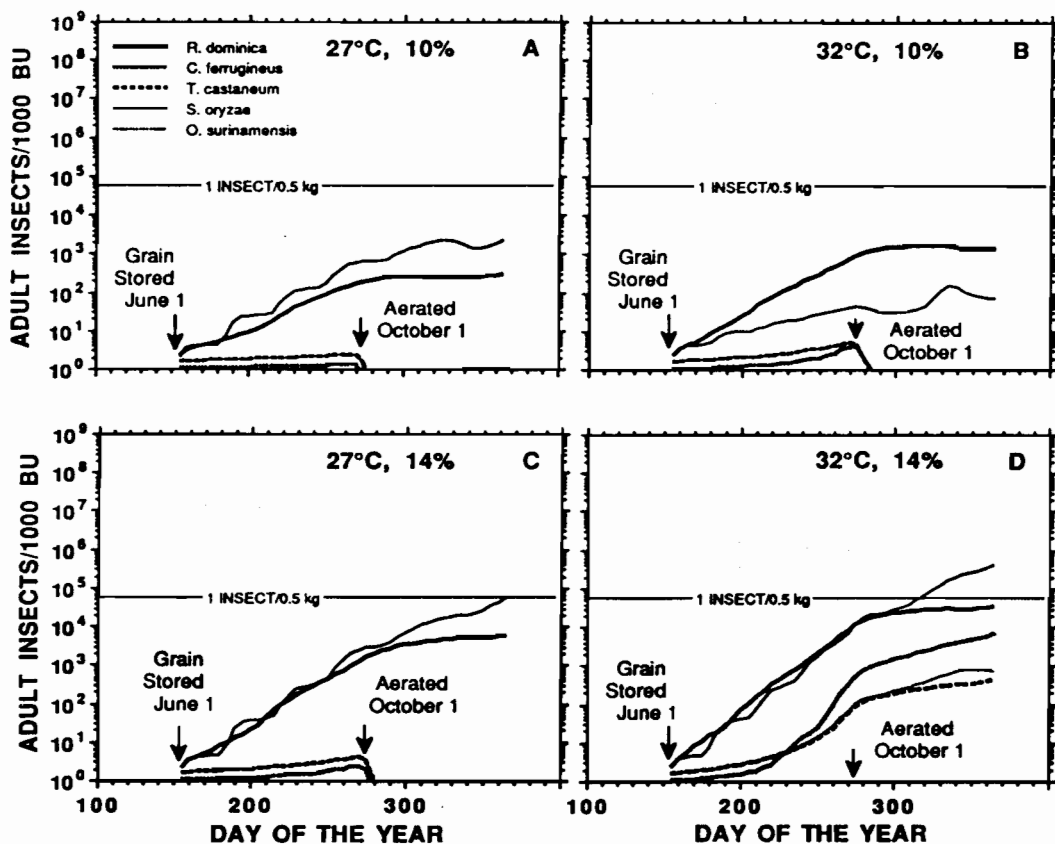


Figure 1. Predicted effects of initial grain temperatures and moisture contents of (A) 27°C and 10%, (B) 32°C and 10%, (C) 27°C and 14%, and (D) 32°C and 14% on the population growth of five species of stored-grain insects with wheat aeration completed on 1 October (from Hagstrum and Flinn 1990).

Moisture Migration in Non-aerated Storages

Grain at the right moisture content and temperature can be stored safely for long periods. However, maintaining grain storage conditions within an acceptable range requires close management (or thermally insulated storages). When grain is stored at safe moisture levels but is not aerated, moisture migration can develop from one part of the storage to another. Moisture migration is caused by significant temperature differences that develop within a non-aerated grain mass. Cold weather causes temperatures in the outer 0.5–1 m (top and sides, and bottoms in storages with ducts or plenum floors) of a grain mass to cool significantly faster than the grain closer to the centre. This temperature differential results in slow-moving convection currents (Fig. 7). Cold, dense air settles

by gravity through the cold, outer grain. The air warms and expands as it moves inward near the bottom of the storage, and then rises in the inner grain mass. As air warms, its relative humidity (r.h.) decreases, and its moisture-carrying capacity increases. For each 10°C rise in temperature, the relative humidity is halved. Air at 0°C and 80% r.h. will drop to 40% r.h. when warmed to 10°C. As this warm, moist air moves up to the grain surface, it cools to its dew point and begins condensing moisture on the colder grain near the surface. For cold grain, such as maize carried over into the summer, convection currents are primarily driven by the solar radiation on the sun-exposed walls. Air rises along the warmed walls of the bin and downward along the cooler shaded walls on the opposite side. In this case, moisture may condense and grain spoil along the shaded walls.

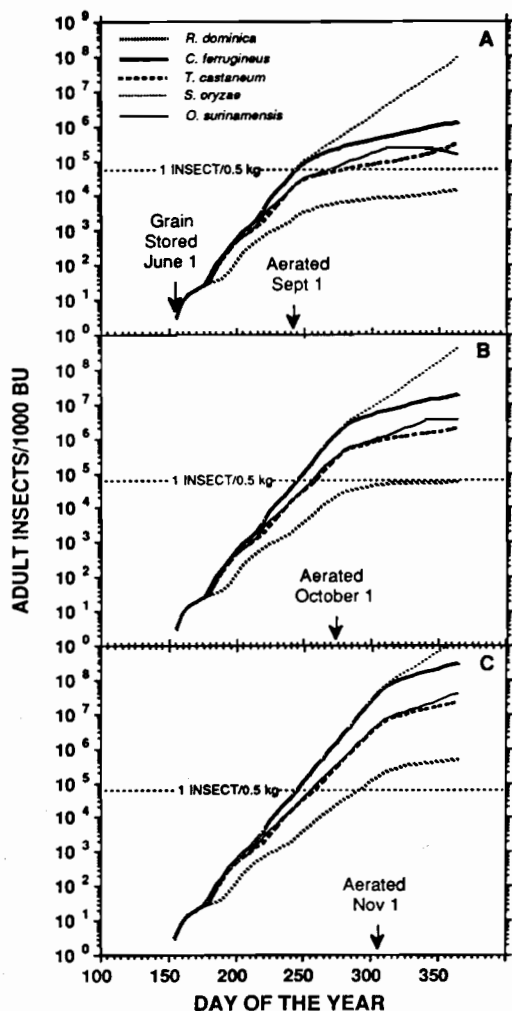


Figure 2. Predicted effects of time of aeration on population growth of five species of stored-grain insects at 32°C and 14% grain moisture content (from Hagstrum and Flinn 1990).

Warm, moist headspace air activates moulds, causing grain to crust and seal-over, especially when grain is left peaked and uncored. Top crusting can occur when warm air is exhausted from the grain mass during cooling in cold weather, and during storage after grains were initially dried to moistures as low as 9 to 11%. This is a typical condition when maize or rice are transferred hot from a dryer into a tempering (dryeration) or cooling bin (in-bin cooling). Significant condensation occurs on bin walls and roofs, and extended fan operation is needed to minimise excessive dripping. Peaked grain has a

larger exposed surface area for moisture to condense on. Increased levels of moisture are also caused by condensation from downspouts, and leaking roofs and hatch covers that allow rain and snow to enter the headspace. The development of “hot spots” in storage is a typical indicator of grain spoilage due to excessive moisture. The grain under the loading spout is more densely packed with fine material and thus more prone to self-heating.

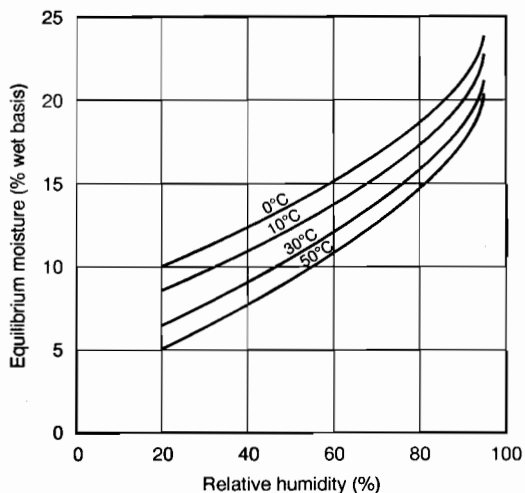


Figure 3. Equilibrium moisture content of yellow dent corn (from Anon. 1992).

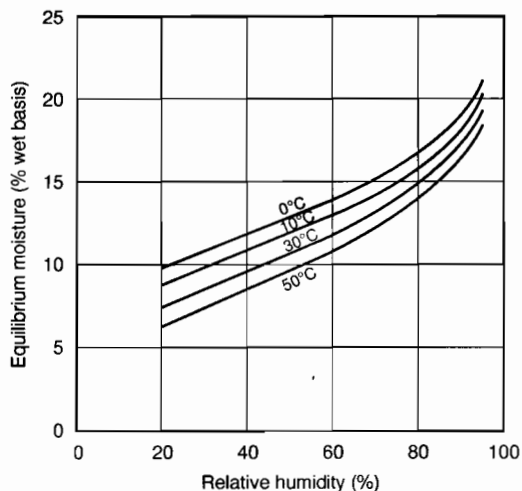


Figure 4. Equilibrium moisture content of rough rice (from Anon. 1992).

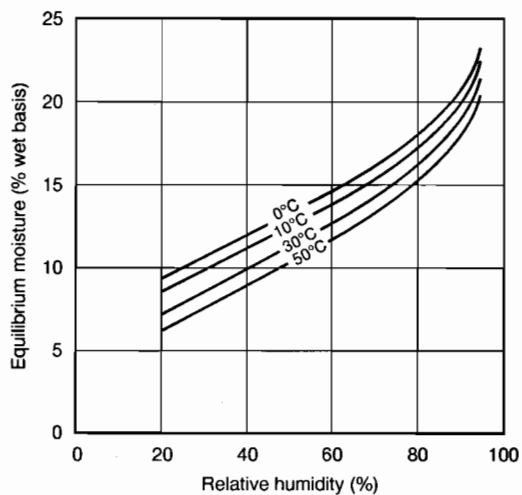
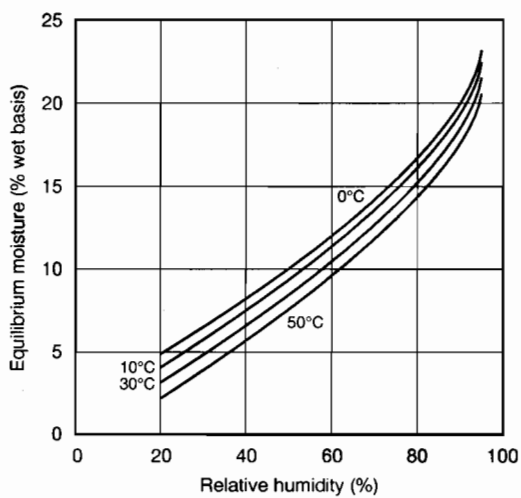


Figure 5. Equilibrium moisture content of soybean (from Anon. 1992).

Figure 6. Equilibrium moisture content of hard wheat (from Anon. 1992).

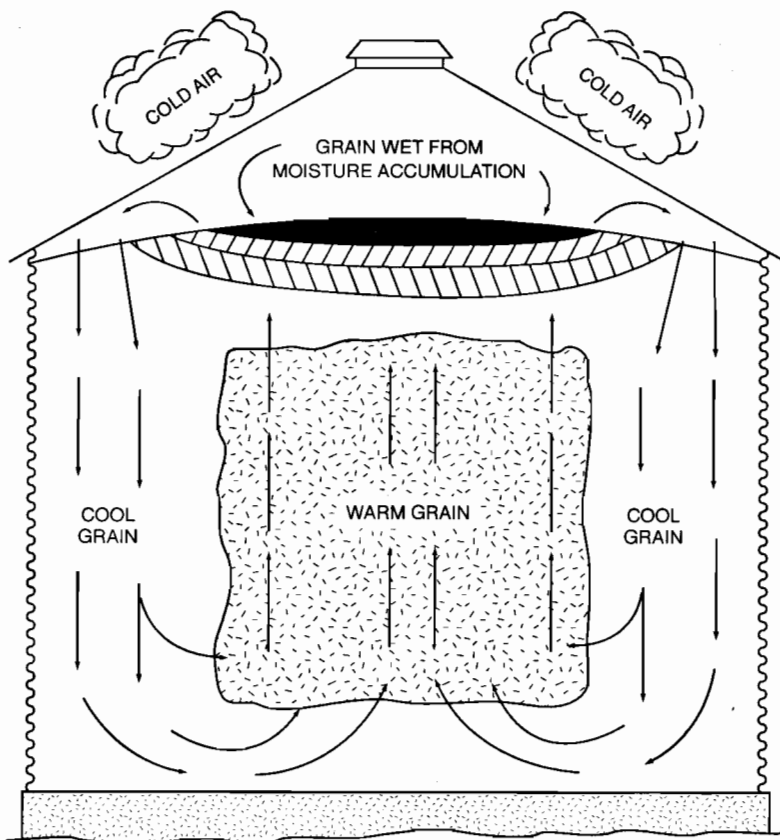


Figure 7. Moisture migration in non-aerated, warm grain when outside ambient temperatures are consistently cold (from Brooker et al. 1992).

Generally it is recommended to maintain grain temperatures within 5–10°C of the average ambient temperature for the geographic location of the storage to minimise the potential for convection currents. Also, sealing the fan inlets when the aeration system is not operating reduces the chance for moisture migration, premature grain warming, and pest and rodent infiltration.

Aeration Systems

An aeration system consists of a fan, an air supply duct (or transition), aeration ducts (or perforated floor), and a fan controller (ranging from a simple on-off switch operated manually to a state-of-the-art computer-based system). The fan can be either centrifugal or axial-flow type, depending on the static pressure and airflow requirements of the grain storage. It is critical that the fan be properly sized to deliver the recommended aeration airflow rate for a particular grain storage. Software tools, such as the FANS program available from the University of Minnesota (Anon. 1995), which includes the curves of over 200 commercially available fans, should be consulted in the design of any new structure, as well as in the verification of any existing aeration system. The air supply duct should be sized so that the duct velocity does not exceed 460–610 m/min to prevent excessive pressure drop in the duct (Brooker et al. 1992). In-bin control systems should be employed to control aeration cooling and natural air/low temperature grain drying (Moreira and Bakker-Arkema 1992). A controller decides if, when, and for how long fan operation is needed.

Figure 8 shows typical aeration supply systems. The air is distributed into the grain via aeration ducts or a perforated floor. Ducts do not distribute the air evenly through the grain. The location and spacing of the aeration ducts are critical because they determine the uniformity of airflow through the grain. If a grain silo is equipped with a fully perforated floor, distribution is more even, provided the grain surface is level and the fines in the grain are either removed by cleaning or coring of the grain, or evenly distributed throughout the grain mass with the help of a good spreader.

In flat storages more than one aeration duct is generally required. The optimal spacing of the ducts is based on the ratio of the shortest to the longest path of the air from the duct to the grain surface. The ratio should be approximately 1.5. Figure 9 illustrates the concept of proper spacing of aeration ducts in flat grain storages. The reader is referred to aeration system design handbooks for more information.

Aeration Controllers

The use of automatic aeration controllers to optimise aeration time should be a widely adopted stored-grain management technology. Simple aeration controllers with hour meters that operate fans based on a thermostat set-point have shown to provide precise grain temperature management. Some managers choose to control both high and low temperatures to keep potential temperature differences between the grain and the outside to within 5–10°C. Automatic fan controllers should control grain temperatures to within 2°C of the controller's thermostat set points. Two to three aeration cycles may be needed to accomplish a desired grain temperature reduction using manually operated fans. With suitable cold air ambient temperatures, automatic systems can reduce grain temperatures by intermittently operating the fan whenever suitable weather conditions prevail. Simple aeration controllers usually pay for themselves in less than one year.

Aeration based on the Seed Wet-Bulb Temperature (SWBT) as defined by Wilson and Desmarchelier (1994) is a strategy that has particular benefit in warm temperate climates for dry grains. The SWBT is determined as a function of the moisture content and temperature of the grain. Fan controllers are set to select ambient conditions to achieve the target SWBT based on meteorological data, or actual local conditions by measuring ambient air temperature and relative humidity. Low temperatures at night can be used to cool the grain, and warm conditions during the day enable the grain to be harvested at low moisture. When low moisture grain is cooled to the SWBT, its dry-bulb temperature is near the mean ambient air dry-bulb temperature. Consequently, the grain will not tend to rewarm when the aeration system is turned off, thereby limiting the temperature difference that drives moisture migration.

Aeration based on the equilibrium moisture content (EMC) of grain is another fan control strategy. However, it has been mostly utilised for conditioning moist grain in a bin to the target moisture content. The EMC strategy involves several possible modifications, such as operating the fan based on a self-adjusting minimum number of hours of daily fan operation that depends on the calendar date, the maximum moisture content of the binned grain, a 3–5% EMC window initially and a smaller one near the end of the drying cycle, or in addition to the EMC window a 5–10°C temperature window with limits on the maximum and minimum allowable temperatures (Moreira and Bakker-Arkema 1992).

Humidistat controls add to the cost of controllers and are not necessary for most bulk storage aeration except possibly in the humid tropics, and where more precise control over grain conditions is required.

Humidistats are difficult to maintain, limit the amount of usable cooling time, and if not properly understood can cause more problems than they solve.

More sophisticated control strategies require not only reliable sensors that are regularly calibrated but also programmable microprocessors that are well understood by the user. Several commercial systems have been available for years. Today's state-of-the-art systems are PC-based and tie control strategies into predictive aeration and storage modeling software (Wilson 1990; Maier et al. 1996).

Aeration of Wet Grains

Aeration is also used to maintain the condition of recently harvested, wet grain before it can be dried. The objective of maintenance aeration is different from that of aeration cooling. Because wet, warm grain heats up and moulds quickly, it can be maintained in reasonable condition in temperate climates for 3–7 days depending on the initial grain moisture and temperature if it is aerated at relatively high air-flow rates of 0.50–1.0 m³/min/t. The practice of

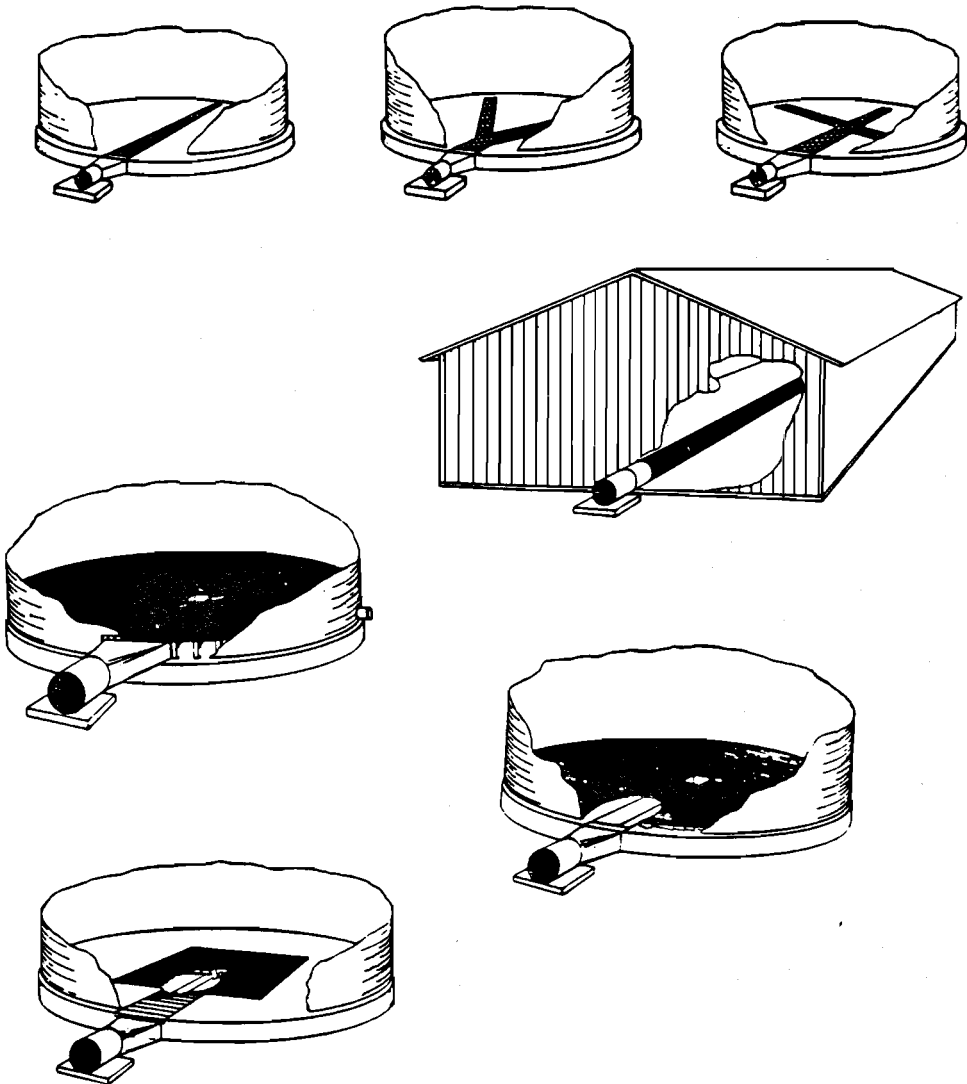


Figure 8. Typical grain aeration systems in circular storage structures (from Brooker et al. 1992).

maintaining the quality of 16–20% moisture content (w.b.) grain by aeration with ambient air decreases the storability of the grain and should be employed with caution (Brooker et al. 1992). Farmers and elevator operators are generally better off expanding drying capacity in order to keep wet holding to the shortest practical time.

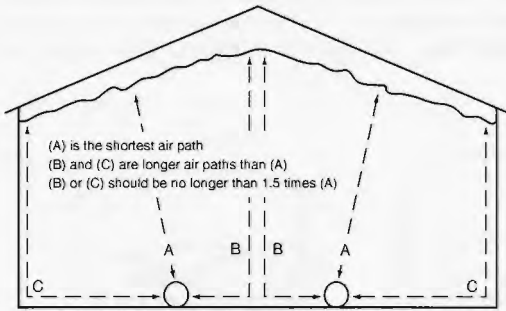


Figure 9. Guidelines for duct spacing in a flat storage (from Brooker et al. 1992).

Chilled Grain Aeration

Chilled grain aeration is defined as the cooling of grain independent of the ambient conditions using a mechanical refrigeration system. In a grain chilling system ambient air is ducted over a bank of refrigera-

tion coils in order to decrease its temperature (Fig. 10). In this process the relative humidity of the air is increased. The chilled air is reheated slightly to match the equilibrium relative humidity of the stored grain. After the initial cool-down, a rechilling cycle is run periodically in order to maintain the grain at the desired temperature. The specifications of a typical grain chiller are given in Table 3. The operation of a typical grain chiller is shown in Figure 11 during a 5-day early-summer period in the midwestern United States. The ambient temperature varied between 10 and 28°C while the chilled-air temperature was maintained between 6 and 7°C. Likewise, the relative humidity of the chilled air remained practically constant at $90 \pm 2\%$ although the ambient air humidity ranged from 25 to 98%.

The ability to control the bin inlet air temperature and relative humidity is especially desirable for food grain storages, such as breakfast cereals, snack food grains, milling grains, etc., where product value is higher. Grain chilling is currently used for storing wheat, maize, popcorn, and rice in several U.S. commercial food processing facilities (Maier 1994). Potential benefits include less liability and improved worker safety due to reduced or eliminated chemical handling; less shrinkage; less spoilage potential; reduced insect damage; and lower drying costs. Recommended grain temperatures for chilled grain storage depend on the grain moisture content, type and end use (Burrell 1982). However, grain temperatures below 15–17°C are usually sufficient to significantly

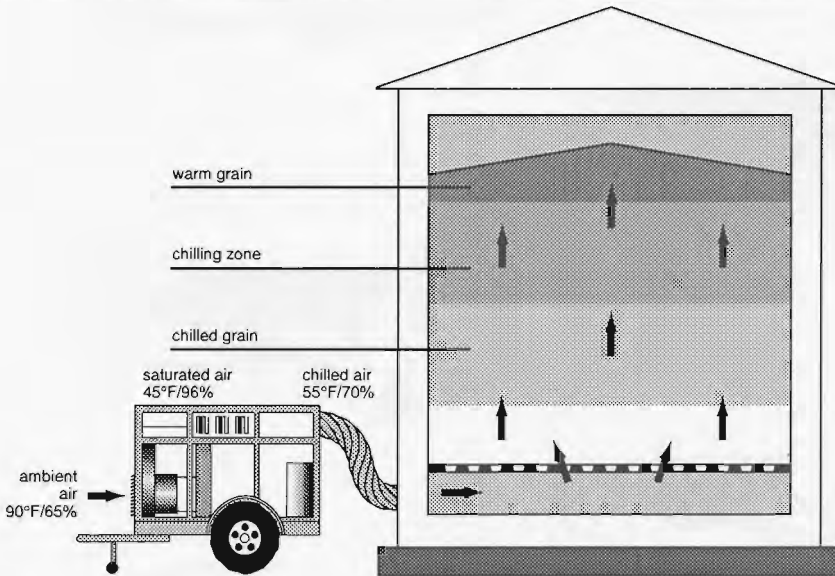


Figure 10. Chilled aeration and conditioning process utilising a mobile grain chiller, which utilises a refrigeration system to control the temperature and relative humidity of the air into the storage bin (55°F \approx 13°C; 90°F \approx 32°C).

slow most insect development. Maier (1992, 1994) extensively reviewed the utilisation of chilled grain aeration in the U.S. and around the world. Rulon (1996) investigated the annual operating costs and amortised net present costs of chilled aeration versus ambient aeration plus fumigation for pest management for U.S. conditions. Chilling has generally lower annual operating costs, and given the current price of commercial chillers in the U.S. can be justified despite the large capital investment required.

Storage Management Using S.L.A.M.

Aeration of stored grain has to be part of an overall preventive postharvest management system involving sanitation, loading, aeration and monitoring (S.L.A.M.) (Maier et al. 1994). Elevator operators and producers must adjust these grain storage management strategies depending on their location, facility, stored product, harvest time, and storage period.

- **Sanitation** before loading grain into a storage requires cleaning bin aeration ducts, floors, and unload auger trenches, where insects thrive on grain dust and fine material; cleaning out insect harbouring locations, such as weeds, trash, and mouldy grain in and around storages; spraying an approved postharvest insecticide around the perimeter of the bin, 1–1.5 m up the outside wall, and

fumigating empty storages; sealing tank, bin and silo base openings including fans to provide barrier protection against insect entry at all locations below the roof eaves [Note: Roof blowers and vents should be left open except when fumigating.]

- **Loading** storages properly involves cleaning, coring, and leveling. Cleaning (screening) removes grain dust and fines that insects and moulds thrive on, and improves aeration. Coring grain bins and silos means operating each storage unload conveyor to pull the peak down at least half way and remove the central core of fines, trash, and foreign material accumulated under the loading spout to make aeration more effective and to remove a major insect attractant. Leveling clean grain using a spreader or removing the peak by coring makes it easier to manage and assures more uniform air-flow.
- **Aeration** to maintain grain temperatures as uniform as possible and as low as practical by managing aeration fans using automatic control. Grain temperatures should be kept below the optimum insect feeding and breeding range of 21 to 32°C.
- **Monitoring** grain in storage using temperature cable thermocouple readouts; scheduled grain and insect sampling; protectant top dressing as needed; fumigation as needed based on economic threshold; and aeration or grain turning when hot spots are detected.

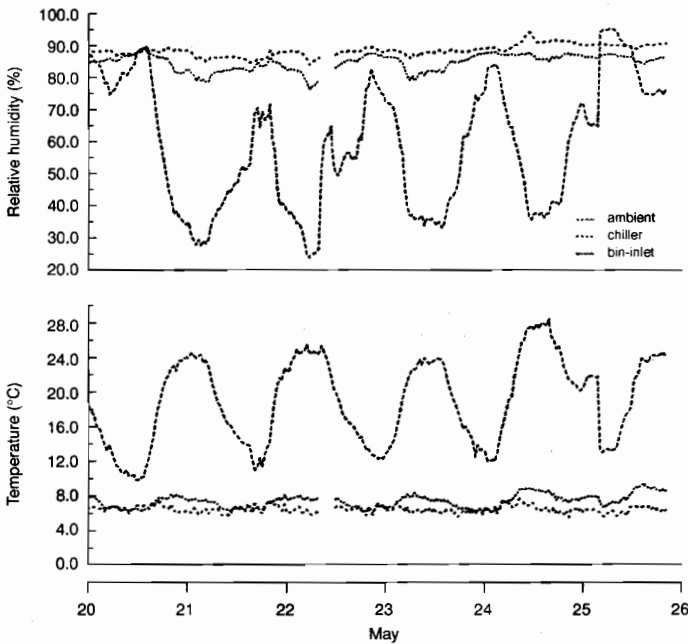


Figure 11. Temperature and relative humidity of the ambient, chilled and bin-inlet air in May 1989 under Midwestern USA conditions (from Maier et al. 1993).

When coordinated, S.L.A.M. management strategies will help to maintain grain quality, minimise marketable moisture weight loss, reduce operating costs, and preserve stored product quality.

Table 3. Design and operating specifications of a commercial^a grain chiller in a temperate climate.

<i>Cooling capacity</i>	
max. capacity under favourable conditions:	500 t/day
average capacity:	330–340 t/day
<i>Flow volume of the cold air</i>	
at a static pressure of 100 mm W.G.:	14200 m ³ /h
300 mm W.G.:	18000 m ³ /h
<i>Compressor cooling capacity (nominal)</i>	
at 30°C condensing temperature and 0°C evaporating temperature:	115 kW
<i>Connected load</i>	
compressor:	25 kW
cold air fan:	30 kW
connected load at nominal cooling capacity:	55 kW

^a GTC3500 manufactured by AAG Manufacturing, Milwaukee, Wisconsin, USA.

Aeration Modeling

Simulation programs can be used to accurately determine the time required to cool a mass of grain. An in-depth analysis of grain aeration can be made with a fixed-bed drying model (Bakker-Arkema 1984). The aeration simulation model chosen in the subsequent case studies assumes steady-state between the grain and air temperatures and humidities. The model is called AERATE, and was developed by Michl (1983); significant modifications to the Michl model were made by Maier (1992) and Maier et al. (1996). The Michl model is similar to the Thompson (1972) fixed-bed grain drying model.

The AERATE program requires information about the desired aeration strategy, the ambient conditions, the bin configuration, and the grain being dried/cooled. The simulation of conventional aeration is accomplished using historic weather data. The hourly temperature and relative humidity values are needed, along with the local barometric pressure. The other moist air parameters are calculated with the help of the built-in psychrometric subroutines. In the chilled aeration operation, it was assumed that the inlet air temperature and relative humidity were supplied by a commercial grain chiller independent of the ambient

conditions. The cooling air temperature and relative humidity to the grain pile were constant at the bin inlet and depended on the desired storage temperature and moisture content of the grain. To prevent insect development a threshold of 15°C grain temperature was chosen (Baur 1984).

The effectiveness of preserving grain quality utilising both ambient and chilled aeration will be illustrated for Thai, Brazilian and U.S. conditions, for both maize and paddy rice.

Case Studies

Case 1: Thailand

Input data for Thailand

In order to assess the potential use of grain chillers in Southeast Asia, the storage of paddy in central Thailand was previously considered by Maier et al. (1993). Simulation was employed to analyse ambient versus chilled aeration of a 15 m diameter and 10 m high steel silo filled with 1000 t of paddy initially at 27–29°C. The silo was assumed to be equipped with a fully perforated floor for uniform airflow through the paddy. Airflow rates in the range of 0.05–0.5 m³/min/t were considered as recommended for the bulk storage of grains by Brooker et al. (1992). Weather data for the central region of Thailand were used. The data were collected by the Rice Research Center in Pathumtani Province for 1988 and 1989 (AIT 1990), and analysed as described by Maier et al. (1993). For the 1000-t bin of paddy, the static pressure drop was determined for rough rice according to ASAE Data D272.2 (Anon. 1992). The calculated value was increased by 10% to account for additional pressure losses due to the perforated bin floor, the connecting duct, the velocity pressure in the duct, and fines accumulation in the grain mass.

In order to maintain the 13% moisture content of the paddy at 15°C, an equilibrium relative humidity of the chilled bin inlet air of 65% was required according to ASAE Data D245.4 (Anon. 1992). The heat loss in the connecting duct was assumed to be 1°C. Thus, the required chilled air temperature was 14°C with a relative humidity of 69%. A summary of the input parameters used in the AERATE grain cooling simulation model is found in Table 4. Simulation results were determined for the wet and dry seasons of 1988 and 1989 for the central region of Thailand.

Results and discussion for Thailand

Ambient aeration. The ambient air temperature and relative humidity ranges and averages are summarised in Table 5. Average temperatures and relative humidities were lower for the dry than the wet seasons. The 1988 dry season was slightly cooler and

wetter than the 1989 season, while the 1988 and 1989 wet seasons were similar in temperature but with 1988 slightly wetter than 1989.

Table 4. Input parameters of the AERATE simulation model for ambient and chilled aeration of 1000 t of paddy under typical Thai conditions (from Maier et al. 1993).

Parameter	Values	
Bin diameter, m	15.0	
Bin height, m	10.0	
Bulk density, kg/m ³	566.0	
	<i>Dry season</i>	<i>Wet season</i>
Initial paddy temperature, °C	27.0	29.0
	<i>Ambient</i>	<i>Chilled</i>
Air temperature	see Table 5	14°C
Air relative humidity	see Table 5	69%
Airflow, m ³ /min/t	0.150	0.148–0.150
Initial paddy moisture, % wb	13.0	13.5

The ranges and final average temperatures and moisture contents of the paddy for both seasons and years are summarised in Table 6 for continuous ambient aeration. The temperature range was wider during the dry than the wet seasons (up to 11.5°C during the 1989 dry season), and the shrink loss was greater during the dry than the wet seasons. The average shrink

losses of the paddy reached 0.9–1.2 percentage points of moisture by the end of the wet season aeration periods, and 1.1–1.4 points by the end of the dry seasons.

The temperature and moisture content of the paddy during four months of continuous aeration between July and October 1988 are shown in Figure 12 (the other three seasons showed similar patterns). The average paddy temperature remained above 25°C at all times, a range (up to 31°C) in which insect development is usually optimum; this verifies the results found by Nour et al. (1988). The repeated adsorption and desorption cycles as evidenced in the bottom layers of the paddy bin during the 1988 wet season tend to increase fissuring of the kernels and decrease head yield. Thus, continuous ambient aeration appears to reduce the quality of the paddy.

To reduce the adsorption and desorption cycles of the paddy, a humidistat set to operate the aeration fan when the relative humidity was below 75% was evaluated. The ranges and final average paddy temperatures and moisture contents are summarised in Table 7 for both seasons and years. Paddy temperature ranges were not significantly different compared to continuous aeration. However, average temperatures at the end of each season were higher by up to 1.6°C in the 1988 dry season and 1.7°C in the 1988 wet season compared to continuous aeration. Shrink losses were increased by 0.3% at the end of the two wet seasons and by 0.7–0.8% at the end of the two dry seasons. Figure 13 shows that the average temperature of

Table 5. Ambient air temperature and relative humidity ranges and averages during the wet (1 July – 31 October) and dry (1 November – 28 February) seasons of 1988 and 1989 for the central region of Thailand (from Maier et al. 1993).

Year	Wet season		Dry season	
	Range	Average	Range	Average
1988	20.7–36.5°C	28.6°C	15.0–35.5°C	25.6°C
	41–100%	79%	42–100%	74%
1989	19.2–36.7°C	28.5°C	14.3–36.0°C	26.3°C
	52–100%	75%	39–100%	72%

Table 6. Ranges and final average temperatures and moisture contents of paddy aerated continuously during the wet and dry seasons of 1988 and 1989 for the central region of Thailand (from Maier et al. 1993).

Year	Wet season		Dry season	
	Range	Final	Range	Final
1988	25.7–30.9°C	29.0°C	20.2–29.5°C	26.5°C
	11.9–13.3%	12.1%	11.2–13.2%	11.9%
1989	24.8–30.1°C	28.9°C	19.6–31.1°C	30.0°C
	11.6–13.0%	11.8%	10.9–13.2%	11.6%

the paddy remained above 26°C for humidistat-controlled aeration during the 1988 wet season (the other three seasons showed similar patterns). However, the daily temperature variation in the grain pile observed during continuous aeration was avoided. The temperature of the bottom layer was higher than that of the top layer during most of the aeration period. This was due to the operation of the fan during high-ambient temperature periods when the ambient relative humidity dropped below 75%.

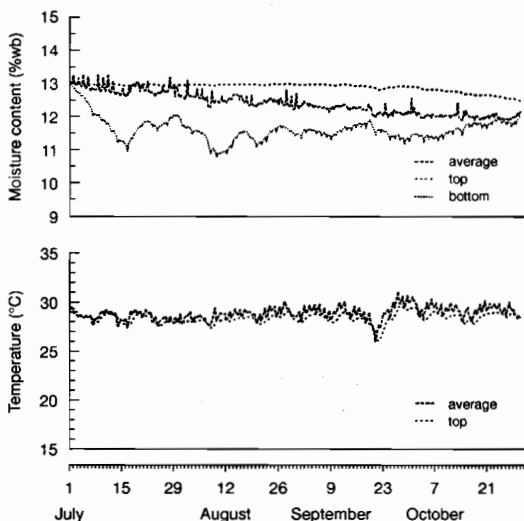


Figure 12. Temperature and moisture content of paddy rice aerated continuously under Thai conditions between July and October 1988 (from Maier et al. 1993).

On the other hand, the humidistat-controlled aeration reduced fan run-time and energy consumption. During the dry storage seasons of 1988 and 1989, 44 and 38% less energy and during the wet season of 1988 and 1989, 64 and 43% less energy were consumed, respectively, than for continuous aeration. The fan operated for 1650 and 1836 hours during the 1988 and 1989 dry seasons, respectively, and for 1062 and 1680 hours during the 1988 and 1989 wet seasons, respectively, compared with 2946 hours during the continuous four-month aeration operations. While the number of cycles of moisture adsorption and desorption during the humidistat-controlled aeration were reduced, the bottom layer reached a moisture content of as low as 9.3% during the 1989 dry season compared with 10.0% for continuous aeration (not shown). Thus, a simple humidistat does not appear to be a desirable aeration controller for use in the humid tropics.

Chilled aeration. Contrast the results in Figures 12 and 13 with those in Figure 14 in which chilled aera-

tion with constant bin-inlet air conditions was used for the average of the two wet seasons. The paddy in the silo was completely chilled to below 20°C within 88 hours, and below 15°C within 144 hours. The moisture content of the bottom layer reached 12.5%, while the top layer was slightly below 13.0%. During the average of the two dry seasons, the chilling time was only 110 hours and yielded similar temperature and moisture profiles. Most importantly, at 15°C and 12.5–13.0% m.c., the paddy can be stored for extended periods in Southeast Asia and elsewhere with a significant reduction in the potential for insect infestation (Baur 1984). Additionally, in order to achieve the desired market moisture content of 13%, the initial paddy moisture could be as high as 13.5% due to the evaporative cooling effect of the chilled air.

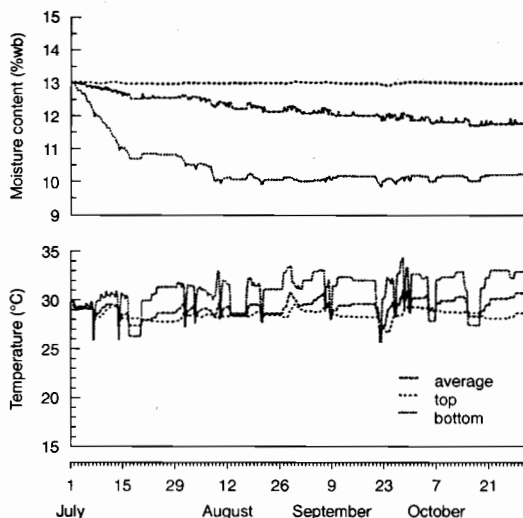


Figure 13. Temperature and moisture content of paddy rice aerated whenever the relative humidity was less than 75% under Thai conditions between July and October 1988 (from Maier et al. 1993).

The average chilling capacity of 167 t/day during the wet season in Thailand was about 50% of the rated average capacity specified by the chiller manufacturer; during the dry season, the actual capacity of 218 t/day was 35% less than the rated one. The energy requirement for chilling to 15°C during the wet season was 7.8 kWh/t compared to 5.9 kWh/t during the dry season, i.e., a decrease of 24%. These results indicate that the commercial grain chiller would not operate optimally in the central region of Thailand. Chiller manufacturers usually equip their units with larger refrigeration capacities to accommodate the higher latent cooling loads in the humid tropics.

Table 7. Ranges and final average temperatures and moisture contents of paddy aerated whenever the relative humidity of the ambient air was less than 75% during the wet and dry seasons of 1988 and 1989 for the central region of Thailand (from Maier et al. 1993).

Year	Wet season		Dry season	
	Range	Final	Range	Final
1988	26.2–30.8°C	30.7°C	20.6–28.1°C	28.1°C
	11.7–13.0%	11.8%	11.1–13.0%	11.1%
1989	24.5–29.9°C	29.8°C	19.7–30.1°C	30.1°C
	11.4–13.0%	11.5%	10.8–13.0%	10.9%

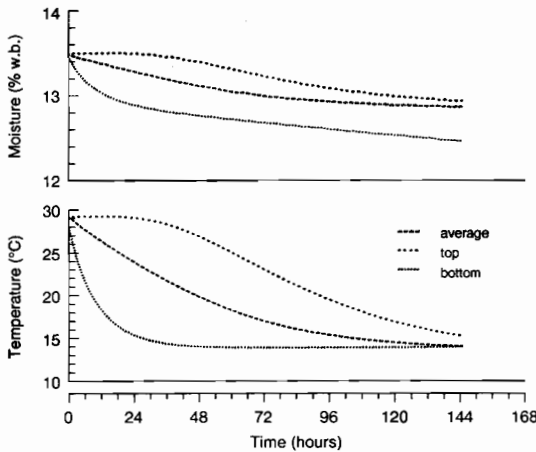


Figure 14. Temperature and moisture content of paddy rice aerated with a grain chiller during the Thai wet season (from Maier et al. 1993).

Summary for Thailand. The cooling of paddy stored under Thai conditions during the 1988 and 1989 seasons showed that ambient aeration could not reduce the average grain temperature below 25°C during either the wet or dry season. Chilled aeration moved a cooling front completely through a 1000 t bin. It lowered the paddy temperature to 15°C, which is the typical insect development threshold, in 110 to 144 hours, depending on the season. However, a commercial grain chiller originally designed for temperate climates would have to have its refrigeration capacity increased by 35–50% to match the fan design airflow rates desired for the humid tropics. Shrink loss due to ambient aeration was higher during the dry than the wet season, and was smallest for chilling with 0.5 percentage points compared to 0.9–1.4 points for continuous ambient, and 1.2–2.1 points for humidistat-controlled aeration. In addition, moisture gradients between the top and bottom layers were minimised by chilling. A simple on–off humidistat set to operate below 75% relative humidity ran

the fan 38 to 64% less than continuous aeration. Although it reduced the effect of adsorption and desorption cycles, it removed up to 0.8 percentage points more moisture from the paddy and did not control the paddy temperature any better than continuous ambient aeration.

Case 2: Brazil

Input data for Brazil

In order to assess the advantage of the use of aeration in Brazil, the storage of maize in the Paraña region was considered by Moreira and Maier (1993). Simulation was employed to analyse conventional and chilled aeration of grain stored at a commercial grain elevator. The maize was stored in a metal silo with a holding capacity of 600 t; the silo diameter was 10.1 m and the fill depth 10.3 m. The maize was harvested on 15 March, dried (if needed) to about 14% m.c. (w.b.), and reached the silo at approximately 25°C. Different aeration schedules were used with the principle aim to cool the grain to below 15°C as rapidly as possible without excessive overdrying.

Two aeration strategies were investigated using ambient air at a flow rate of 0.11 m³/min/t using a 5 hp fan: (1) continuous aeration, and (2) aeration whenever the relative humidity of the ambient air was below 75%. The grain temperature and moisture content in the silos were simulated for March through September in Paraña, Brazil, over a four-year period (i.e., 1989–1992) using ambient weather conditions recorded every three hours. For the chiller, the ambient air was cooled and dehumidified to a temperature of 15°C, and a relative humidity of 65% for maize. The airflow rate during chilled aeration was also 0.11 m³/min/t.

Results and discussion for Brazil

Ambient aeration. The weather conditions for March–September 1989–1992 in the south of Brazil are summarised in Table 8. The four-year average temperature was 20°C with a range of 2.1 to 32.8°C, the four-year average relative humidity was 75.0%

with a range of 30.1 to 100%. Figure 15 shows the plot of the 1991 weather conditions for March–September.

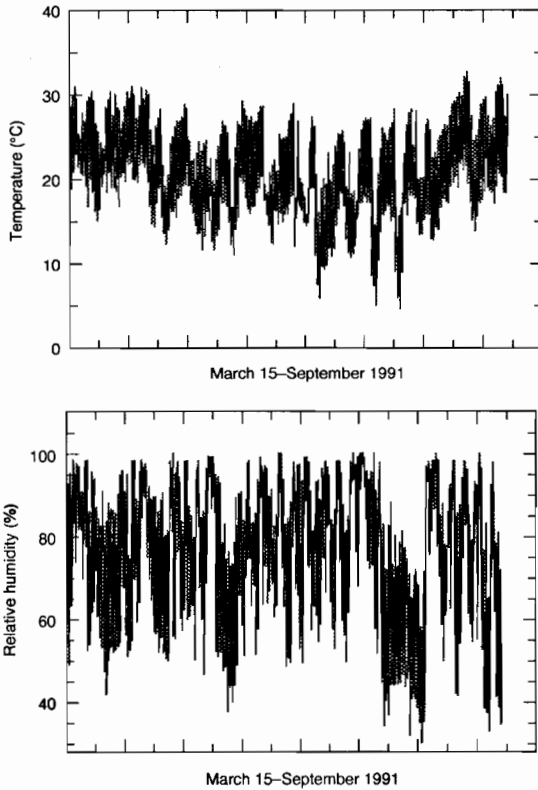


Figure 15. Ambient temperature (a) and relative humidity (b) in Paraña, Brazil between 15 March and 15 September 1991 (from Moreira and Maier 1993).

Table 8. Average, maximum and minimum ambient temperature and relative humidity in southern Brazil between March–September 1989–1992 (from Moreira and Maier 1993).

Year	Temperature (°C)			Relative humidity (%)		
1989	19.7	31.8	2.1	73.9	100	29.5
1990	19.2	32.8	2.8	76.4	100	30.1
1991	20.7	32.8	5.1	70.5	100	27.7
1992	19.5	31.3	3.1	79.1	100	31.1

Figures 16 and 17 show the average temperature and moisture content of the maize for the March 15–September 15, 1989–1992 storage periods for the continuous and humidistat-controlled ambient aeration strategies. Continuous aeration resulted in lower average grain temperatures and in less over-drying of the

maize (Table 9). However, grain temperatures remained above 20°C for 1.5–3 months for continuous versus 2–4.5 months for intermittent aeration. Temperatures reached 15°C and below in two and one of the four seasons, respectively. It took longer for the maize to reach the desired storage temperature using intermittent aeration. The 1992 season was a rather humid one with the least moisture shrink for both strategies. Intermittent aeration resulted in 0.1 to 0.4 percentage points over-drying of the maize. However, the bottom grain layers shrank by as much as 1.8 percentage points compared with 1 point maximum shrink for continuous aeration. However, energy consumption was on average 40% less for intermittent aeration (Table 10).

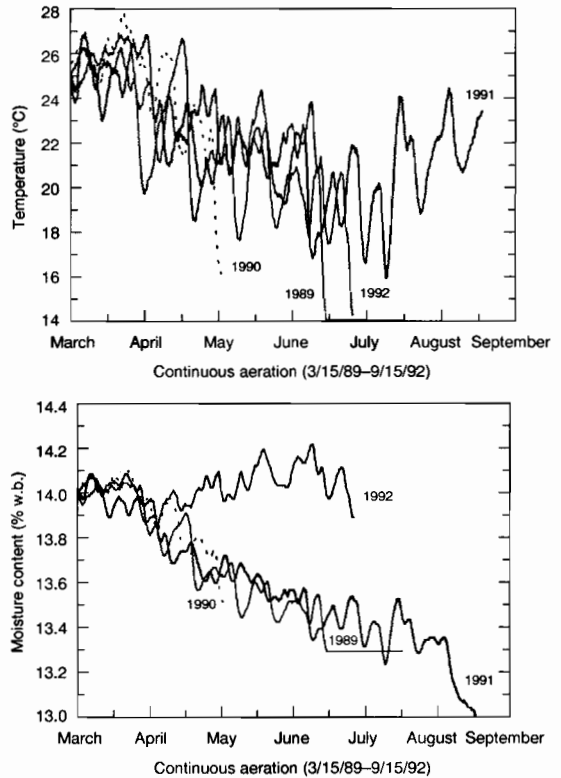


Figure 16. Temperature (a) and moisture content (b) of maize aerated continuously under Brazilian conditions between March–September 1989, 1990, 1991 and 1992 (from Moreira and Maier 1993).

Chilled aeration. Figure 18 shows a sharp contrast among the results when chilled aeration with constant air-inlet conditions is compared with the conventional aeration systems for maize (similar results were obtained for the other years). The maize in the silo cooled to below 20°C within 7 days, and below 15°C within 15 days. The final average moisture content of

the maize in the silo was reduced by less than 0.3% during the cooling process.

Energy consumption was on average 4509 kW independent of the inlet temperature changes (Table 10). This was on average 19.9% more energy than for continuous aeration, and 100% more than for intermittent aeration. Nevertheless, even in warmer years the chiller was able to reduce the grain temperature from the bottom to the top of the silo uniformly to the desired value in shorter periods of time than with ambient air.

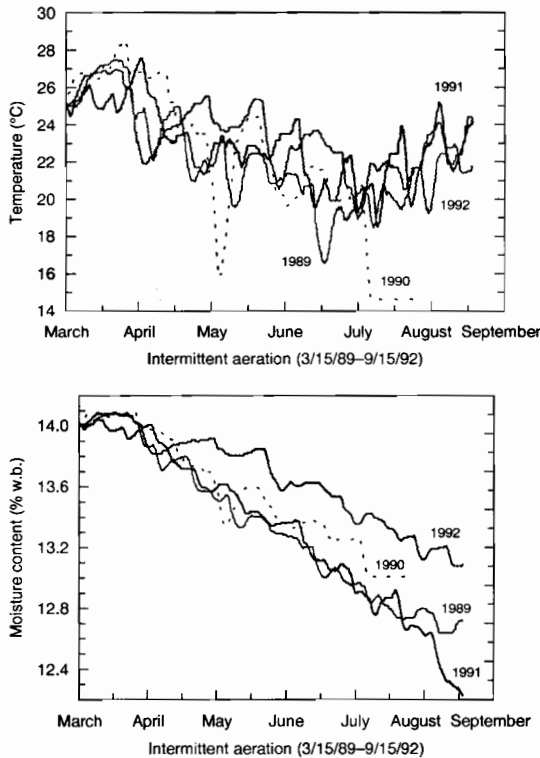


Figure 17. Temperature and moisture content of maize aerated when relative humidity was less than 75% under Brazilian conditions between March–September 1989, 1990, 1991 and 1992 (from Moreira and Maier 1993).

Summary for Brazil. The cooling of maize stored under Brazilian conditions during 1989 through 1992 mid-March to mid-September showed that ambient aeration could not reduce average grain temperatures consistently below 15°C in a predictable time. Chilled aeration cooled the 600 t steel bins within 15 days. Shrink loss was highest for intermittent ambient aeration and least for chilling. Average energy consumption for chilling of 7.5 kWh/t were only 20% higher than for continuous ambient aeration. This would

appear to be acceptable given the additional savings that can accrue due to a reduction in the need for insecticides and fumigants.

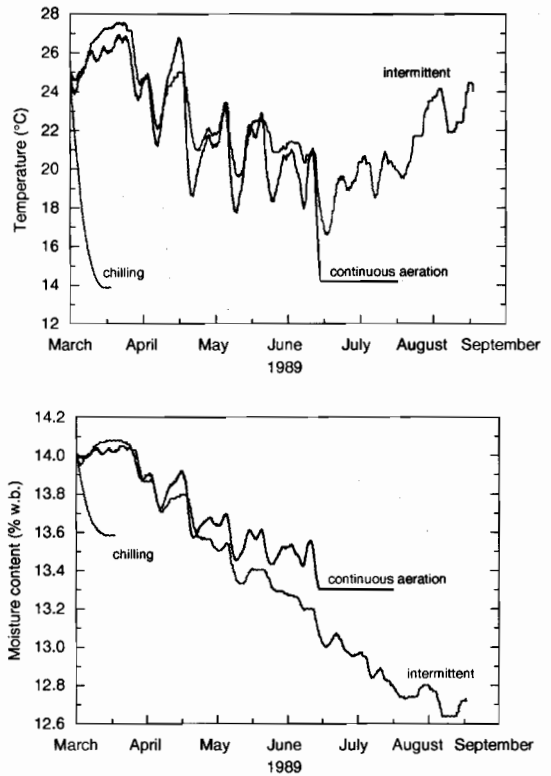


Figure 18. Temperature and moisture content of maize aerated continuously, when relative humidity was less than 75%, and using chilled aeration under Brazilian conditions between March–September of 1989 (from Moreira and Maier 1993).

Case 3: United States

Input data for the United States

In order to assess the advantage of the use of grain chillers in the United States, the storage of paddy rice and food maize in the Corpus Christi, Texas area was considered at two commercial food-grain elevators by Maier et al. (1993). The rice was stored in 60 concrete silos with a holding capacity of 91 t each; the silo diameter was 3.7 m and the fill depth 15.3 m. The maize was stored in 36 concrete silos with a holding capacity of 1200 t each; the silo diameter was 9.1 m and the fill depth 23.8 m. The rice and maize were harvested in late July, dried (if needed) to about 13% (w.b.), and reached the silos at approximately 38°C. Four aeration strategies were investigated using ambient air at a flowrate of 0.1 m³/min/t: (1) continuous

aeration, (2) aeration whenever the relative humidity of the ambient air was below 75%, (3) aeration between 10 a.m. and 4 p.m., and (4) aeration between 10 pm. and 4 a.m.

The chilling of the grain was set to provide a bin inlet air temperature of 15°C, and a relative humidity of 58% for maize and 63% for rice. The airflow rate during chilled aeration was a constant 0.1 m³/min/t. Both ambient and chilled aeration were analysed during the warmest storage months (i.e., August, September and October) over a three-year period (i.e., 1988–1990). Weather conditions were recorded every three hours (NOAA 1988, 1989, 1990).

Results and discussion for the United States

Ambient aeration. The weather conditions for Corpus Christi, Texas, during August and October are warm and humid. The 28-year average temperatures

(i.e., 1962–1989) for August were 28.6°C, for September 27.0°C, and for October 23.3°C. Ambient temperatures in 1988 ranged from 13.3 to 38.9°C, and the relative humidity from 27 to 100% during August through October.

There was little difference in the stored grain temperatures among the three seasons and between the two grains (Tables 11 and 12). The average grain moistures in the silos remained at 12.5±0.5% w.b., and the average grain temperatures for the summer were 28±2°C. Continuous aeration resulted in less overdrying of the rice and maize in the bottom layers of the silos, and in the lowest average grain temperatures (except for the 10 pm.–4 a.m. case), and has the smallest differentials in moisture content. Thus, it is the recommended strategy of aeration among the four investigated for food maize and rough rice in the warm and humid coastal region of Texas.

Table 9. Average grain temperatures and moisture contents, and ranges for the regular and chilled aeration of maize in southern Brazil between March–September 1989–1992 (from Moreira and Maier 1993).

Strategy	Year	Temperature (°C)		Moisture (% w.b.)	
Continuous	1989	20.5	26.8–14.2	13.6	14.0–13.3
Less than 75% r.h.		22.3	27.5–16.6	13.3	14.1–12.7
Chilled ^a		17.1	25.0–14.8	13.7	14.0–13.6
Continuous	1990	20.6	27.9–16.1	13.7	14.1–13.5
Less than 75% r.h.		22.1	28.5–14.6	13.6	14.1–13.0
Chilled ^a		17.4	25.0–14.8	13.7	14.0–13.6
Continuous	1991	20.6	27.8–16.1	13.6	14.1–13.0
Less than 75% r.h.		22.1	26.9–16.1	13.3	14.1–12.2
Chilled ^a		17.3	25.0–14.8	13.7	14.0–13.6
Continuous	1992	21.1	26.3–14.4	14.1	14.2–13.8
Less than 75% r.h.		23.3	26.9–18.9	13.7	14.1–13.1
Chilled ^a		17.3	25.0–14.8	13.7	14.0–13.6

^a It was assumed that the chilled grain was maintained at these average conditions with intermittent rechilling during the 4-month storage period.

Table 10. Operating hour and power consumption of fans and chiller unit for the regular and chilled aeration of maize in southern Brazil between March–September 1989–1992 (Moreira and Maier 1993).

Year	Continuous		When r.h. < 75%		Chilling ^a	
	Operating	Power	Operating	Power	Operating	Power
1989	2778	3500	1986	2502	360	4508
1990	1659	2090	1377	1735	372	4656
1991	4440	5594	2376	2994	345	4331
1992	3066	3863	1392	1754	366	4539
Avg.	2986	3762	1783	2246	361	4509

^a Only includes energy consumed for initial cool down of maize.

Table 11. Average grain temperatures and moisture contents, and ranges, for the regular and chilled aeration of rice in Texas between August–October 1988 (Maier et al. 1992).

Strategy	Temperature (°C)		Moisture (% w.b.)	
	Average	Range	Average	Range
Continuous	27.8	21.1–37.8	12.8	12.2–13.2
Less than 75% r.h.	29.3	24.0–37.8	12.1	11.6–13.0
10 a.m.–4 pm.	29.3	24.7–37.8	12.3	11.9–13.0
10 pm.–4 a.m.	26.9	21.0–37.8	12.9	12.7–13.3
chilled ^a	15.2	15.0–15.5	12.9	12.8–12.9

^a After 124 hours of chilling.

Table 12. Average grain temperatures and moisture contents, and ranges, for the regular and chilled aeration of maize in Texas between August–October 1988 (from Maier et al. 1992).

Strategy	Temperature (°C)		Moisture (% w.b.)	
	Average	Range	Average	Range
Continuous	28.3	21.9–37.8	13.0	12.4–13.6
Less than 75% r.h.	29.6	24.5–37.8	12.3	11.8–13.0
10 a.m.–4 pm.	29.8	25.2–37.8	12.5	12.0–13.0
10 pm.–4 a.m.	27.6	21.8–37.8	13.0	12.8–13.4
Chilled ^a	15.2	15.1–15.5	12.9	12.9–13.0

^a After 154 hours of chilling.

Aeration from 10 pm. to 4 a.m. resulted in the lowest rice and maize temperatures, i.e., about 21°C in 1988 (Figure 19). However, an excessively large variation in the moisture contents developed in the silos. The bottom rice and maize layers absorb up to 1.5% of moisture over the 3-month storage season. Aeration from 10 a.m. to 4 pm., and under conditions of less than 75% relative humidity, resulted in excessive overdrying of the bottom layers of the rice and maize in the silos, i.e., by as much as 2% moisture.

Chilled aeration. The results for the various ambient aeration strategies contrast sharply with those for chilled aeration with constant air-inlet conditions for rice and maize. The rice in the silo was cooled to below 25°C within 54 hours, and below 15°C within 124 hours (Tables 11 and 12). Due to the evaporative cooling effect, the initial rice moisture content could be as high as 13.8% to achieve a desired market moisture content of 13.0% at the end of the cool-down period. The moisture content of the entire pile was within 0.1%. The final temperature gradient between the bottom and top layers was less than 0.5°C.

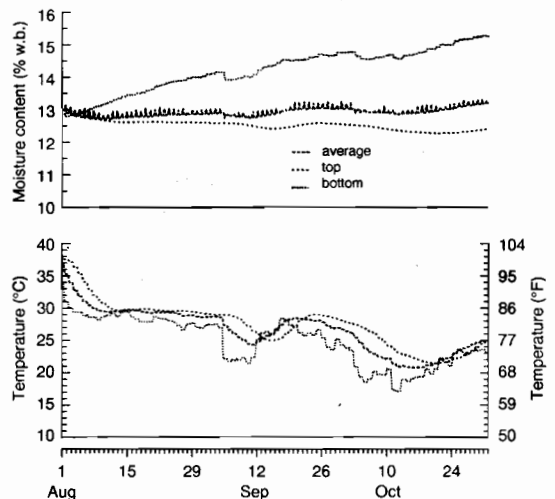


Figure 19. Temperature and moisture content of rice aerated daily from 10 pm. until 4 a.m. under Texas conditions between August and October 1988 (from Maier et al. 1993).

The cool-down of the larger-sized maize silo to below 15°C is completed in 154 hours; the maize temperature dropped below 25°C within 66 hours of chilling. The moisture content of the maize was about 13.0% at the end of the cool-down period. The moisture content differential between the bottom and top layers was less than 0.1%, and the final temperature gradient less than 0.5°C. It is noted that, depending on the capacity of the commercial grain chilling unit, multiple silos can be chilled at the same time when appropriate aeration ducting is used. Most importantly, at 15°C and 12.5–13.0% m.c., the rice and maize can be stored indefinitely in Texas, with a significant reduction in the potential for insect infestation (Baur 1984).

Summary for the United States. Ambient aeration of rough rice and food maize during the summer months (August–October), could not lower the average grain temperature below 28°C in Texas. Of the four conventional aeration strategies investigated, continuous aeration performed best since it resulted in the smallest moisture losses and gradients in the commercial rice and maize silos. Time-clock and upper-limit relative humidity control of regular aeration led to the partial overdrying or underdrying of grain in a silo. Chilled aeration with properly-sized equipment was able to lower the rice and maize temperatures in the commercial silos to below 15°C within a 120–160 hour period. Chilled aeration also prevented excessive moisture losses and maintained the moisture content of silo-stored rice and maize uniformly at 13% (w.b.).

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Conference Summary and Recommendations

Grain that is not dried after harvest is rapidly spoiled by moulds, heating, and insects. The longer drying is delayed, the greater will be the loss of food for humans and feed for animals. Eventually, the whole crop may be destroyed.

Grain drying is thus an important topic for all agricultural countries, and is a special problem in countries such as Thailand where at least one harvest occurs during the wet season. To satisfy the food needs of an ever-growing world population, not only must production of staple grains such as rice, maize, and wheat be increased, but also the losses that occur after harvest must be reduced.

This international conference dedicated to global sharing of knowledge on grain drying was hosted at the Food and Agriculture Organization (FAO) of the United Nations Regional Office for Asia and the Pacific in Bangkok. The conference was officially opened by Mr A.Z.M. Obaidullah Khan, Assistant Director General and FAO Regional Representative for Asia and the Pacific.

The conference, funded by the Australian Centre for International Agricultural Research (ACIAR) and FAO, and organised by the ASEAN Food Handling Bureau (AFHB), was attended by over one hundred engineers, biologists, economists, and other specialists from more than twenty countries around the world. It was organised under the banner of the Group for Assistance on Systems relating to Grain After-harvest (GASGA), an international technical advice group of which FAO is a member. The conference provided an opportunity for grain drying, handling, and storage specialists to come together and share their expertise and experience.

The problems of grain drying are technical, economic, social, and sometimes political. The technical solution to the problem of grain drying in the wet season when sun drying is often not possible is to introduce mechanical dryers—machines that burn oil or other fuels to produce heat for drying. However, those needing the dryers are often poor, small farmers who cannot afford to buy them or to pay a fee for their use. Thus, many governments and international agencies have been exploring means of overcoming this problem and extending the use of grain dryers in the farming sector.

Presentations made at this conference highlighted that much progress has been made in grain drying in the Asian region over the past ten years. The results of research have led to the design and construction of efficient dryers that match the scale of operations of farmer groups and co-operatives. Larger traders servicing export markets are adopting a two-stage drying strategy developed by collaborating teams in Australia, the Philippines, Thailand and, more recently, Vietnam, in research sponsored by ACIAR.

A breakthrough in Thailand over the past few years has been the development and commercialisation by King Mongkut's Institute of Technology Thonburi and the Rice Engineering Supply Co. Ltd of a fluidised-bed machine for rapid drying of wet paddy and maize. Units of these machines have been sold to grain traders in Thailand and many more are on order. There is also interest from other countries, and two units have already been sold in Indonesia.

In the Philippines, mobile flash dryers developed by researchers are being distributed to farmer co-operatives throughout the country as part of a government program to improve grain production.

Another aspect of grain drying that has received much attention is the use of cheaper, alternative fuels for grain drying machines. Research on the combustion of paddy husks, a material once treated as waste, has led to the development of efficient rice-husk burners pro-

ducing heat for grain drying. Vietnamese researchers have built their own fluidised-bed dryers, based on the Thai design mentioned above, but using rice husks as the energy source for drying. The need to minimise emissions of greenhouse gases is also being addressed in the designs of new grain drying strategies.

International trade in staple food and feed grains—an area of considerable interest to Thailand, the world's largest rice exporter—has been a driving force for improvements in grain drying. International markets demand grain of the highest quality and appropriate drying is recognised as the crucial first step in preserving grain quality after harvest. A problem for designers of grain dryers has been lack of information on quality standards in different countries in the Asian region. Participants in the conference in Bangkok committed themselves to gathering this information for eventual publication. Also, the attention of participants was drawn to the existence of a draft international standard (ISO/DIS 11520-1) covering 'Agricultural grain dryers—determination of drying performance', published by the International Organization for Standardization. A outline of the content of the draft standard appears after this conference summary. Adoption of the testing protocols promoted by the standard could lead to further improvements in the performance of grain drying equipment.

In closing the meeting, conference chairman Dr Bruce Champ, noted that presentations and discussions during the week had highlighted that there was a general recognition and acceptance in the grain industries of Asia of the need for appropriate drying technology to maintain quality and enhance international trade in grains. In the commercial sector at least, the adoption of drying technology was self-sustaining. However, the challenge remains to bring the benefits of new knowledge in grain drying to greater numbers of the small farmers who are the main grain producers of Asia. The conference recommended that research and extension agencies continue to explore means for enhancing levels of adoption of appropriately scaled and cost effective drying systems by co-operatives and farmer groups, and that governments foster grain standards and grading systems that provide financial incentives to farmers to dry their crop.

International Standards for Agricultural Grain Dryers

The International Organization for Standardization has drafted standards for the determination of drying performance of agricultural grain dryers (ISO/DIS 11520-1). Part 1 of this protocol concerned the general issues involved and the areas covered are outlined in the following summary:

This Standard describes methods for evaluating the drying performance of continuous flow and batch grain dryers. The methods specified are for determining the evaporation rate which the machines concerned are able to achieve under the steady state conditions prevailing during the tests. Methods for correcting observed performance to other input and standard ambient conditions are described.

For continuous flow dryers the basis of the standard is to monitor the dryer during a relatively short period with steady state conditions fully established, rather than over a long period with fluctuating conditions. For batch dryers the basis is to monitor the dryer during a full cycle of operation. This approach allows the dryer to achieve an evaporation which is maximum for the test conditions, allows comparison of results between different dryers and enables the results to be corrected to specified input and standard ambient conditions.

Normative references are given to other International Standards which through reference in this text constitute provisions of this International Standard.

The text is prefaced by a series of *definitions* of drying terms and parameters by a list of the *symbols and subscripts* that identify the various quantities being measured and the *units* of measurement involved.

The performance required of test *instrumentation* is specified. This covers sensors for air properties—air temperature, air humidity, static pressure and barometric pressure; for grain properties—moisture content and mass; and for energy consumption either from electricity or fuel combusted in situ.

The *preparations necessary for testing* are outlined commencing with recognition of the nominal dryer specifications, requisition of appropriate amounts of grain, and installation of the sensors for measuring the temperature of the drying air, the cooling air, the air inlet to the heater and the exhaust air, the humidity of the inlet air for drying and cooling, the grain temperature, and air static pressure across the grain bed(s) and fan(s).

Procedures for *grain sampling* before and during tests are detailed specifying sample numbers and size, choice of sampling points, frequency of sampling for both continuous flow and batch dryers, properties to be measured and methods for their measurement, the actual conduct of sample analyses whether for temperature, moisture content, or germination, and finally for determination of grain mass and any loss in the exhaust airstream.

The sequences to be followed *during testing* are given for continuous-flow and batch dryers incorporating routines, during start up, the stabilisation period to steady state operation for continuous-flow dryers, and the test period itself.

Finally, methodology for *calculation of results* is provided. For continuous-flow dryers this involves estimation of the mass flow of the grain, its residence time in the dryer and the input moisture content in addition to the performance data common to both continuous-flow and batch dryers—evaporation rate, electrical energy consumption, thermal energy consumption from either direct or indirect heating, and thus specific thermal energy consumption and specific total energy consumption. Serial measurements are allowed for in calculation of means and their deviations.

The results are presented in a *test report* which includes a specification of the dryer on which the test is made, a description of the installation, specification of the fuel used and the input grain, and a table of results which summarises the performance of the machine (detailed in Annex E) and includes additionally measured data, graphs and other calculated data.

A series of annexes provide additional information:

ANNEX A (Normative) *Correction to standard conditions* specifically changes in air density with barometric pressure and temperature; and power, energy and fuel consumption from both electrical and direct and indirect thermal sources.

ANNEX B (Informative) *Estimation of uncertainty of derived measures of performance* by calculation of means, standard deviations, and standard errors of the means of serial measurements.

ANNEX C (Informative) *Checklist* in preparation for dryer testing covering on-site facilities, the dryer specification and capacity, measurement of fuel consumption, grain quantity and quality, sensing and measuring systems, and grain sampling.

ANNEX D (Informative) *Airflow measurement and calculations* by both direct and indirect methods, including derivation of formulae for apportioning air volume flow between drying and cooling beds, effect of standard inlets cones on airflow and estimation of humidity of exhaust air.

ANNEX E (Informative) Example format for test reports for both continuous-flow and batch dryers.

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