A mathematical model, with cost implications, for predicting temperatures in seed stores (ODNRI Bulletin No. 16)

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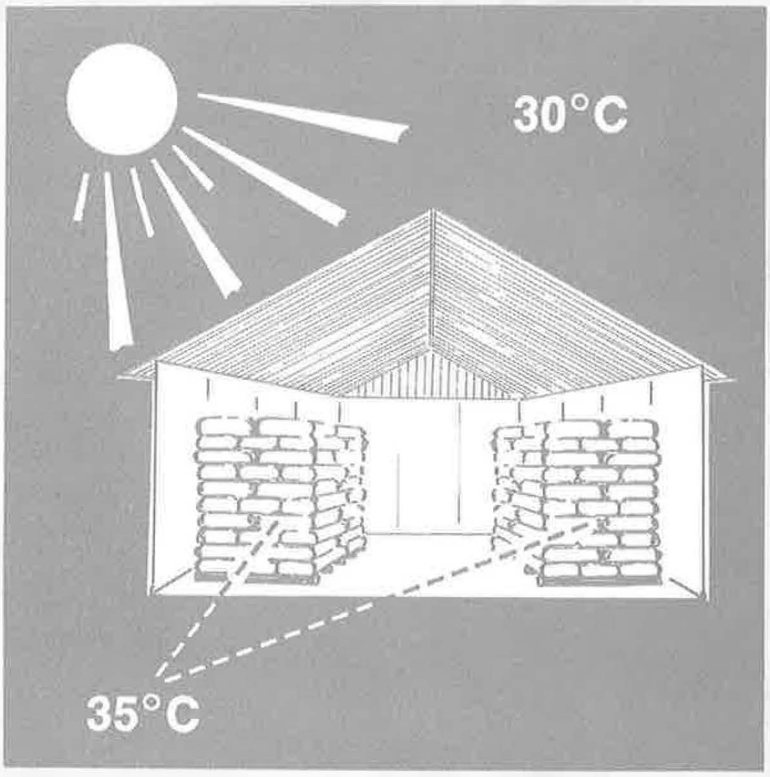

OVERSEAS DEVELOPMENT
NATURAL RESOURCES INSTITUTE
BULLETIN

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A MATHEMATICAL MODEL, WITH COST IMPLICATIONS, FOR PREDICTING TEMPERATURES IN SEED STORES

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A. J. K. BISBROWN AND J. FARRINGTON

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SUMMARY

Mathematical relationships are derived between climatic and design factors in seed stores using heat balance equations modified for tropical seed storage. A computer program has been written for the Hewlett Packard 9645 to make calculation easy; this incorporates data banks of the required parameters for common store building materials and for typical tropical climates. This program has been partially verified for grain in Sri Lanka using field data. Results from program case studies highlight the relative importance of different elements of warehouse design. For seed stores, the program employs viability equations to provide least-cost combinations of warehouse cladding and seed drying regimes under varying conditions of climate and building design. In a typical 1,000-tonne seed store use of aluminium roofing and concrete block walls instead of corrugated steel cladding can save over £12,000 a year, if both drying costs and annualized building costs are taken into account.

RESUME

Des relations mathématiques ont été établies entre des facteurs climatiques et conceptuels en matière d'entrepôts de semances au moyen d'équations du flux thermique, modifiées pour le stockage des semences tropicaux. Un programme informatique a été conçu pour le modèle Hewlett Packard 9645 afin de faciliter les calculs; ce programme comporte des banques de données sur les paramètres requis pour les matériaux courants destinés à la construction d'entrepôts ainsi que pour des climats tropicaux types. Une vérification partielle de ce programme a été effectuée pour des grains au Sri Lanka en utilisant des données au site. Les résultats de cas pratiques soulignent l'importance relative de différents éléments de conception d'entrepôt. En ce qui concerne les entrepôts de semences, le programme comprend des équations de viabilité afin de fournir les moindres combinaisons de coûts de plaques pour entrepôts et de rêgimes de séchage des semences dans diverses conditions climatiques et de conception de bâtiments. Pour un magasin de semences type, d'une capacité de 1.000 tonnes, l'utilisation d'un toit en aluminium et de murs en aggloméré de béton au lieu de plaques en tôle ondulée peut faire économiser plus de 12.000 livres sterling par an si les coûts de séchage et les coûts immobiliers annuels sont pris en compte.

RESUMEN

Se establecen relaciones matemáticas entre factores climáticos y de diseño en almacences de semillas, utilizando ecuaciones de termoequilibrio modificadas para el almacenamiento de semillas tropicales. Para facilitar los cálculos, se ha preparado un programa para el ordenador Hewlett Packard 9645, que incorpora bancos de datos de los parámetros requeridos para materiales comunes de edificios de almacenes y para climas tropicales típicos. El programa h sido parcialmente verificado para granos en Sri Lanka, utilizando datos obtenidos sobre el terreno. Los resultados de estudios de casos han puesto de relieve la relativa importancia de distintos elementos del diseño de almacenes. Por cuanto respecta a los almacenes de semillas, el programa utiliza ecuaciones de viabilidad para proporcionar combinaciones de costes mínimos de regímenes de revestimientos de almacenes y de secado de semillas, bajo condiciones diversas de clima y diseño de edificios. En un almacén típico de semillas de 1.000 toneladas, el empleo de tejado de aluminio y paredes de bloques de normigón, en vez de revestimiento de acero ondulado, puede proporcionar ahorros superiores a las £12.000 al año, cuando se tienen en cuenta los costes de secado y los costes annualizados del edificio.

A mathematical model, with cost implications, for predicting temperatures in seed stores

INTRODUCTION

In a warehouse for durable crops, the 'in-store' temperatures and relative humidities (RH) are important because these affect produce quality during storage. High in-store temperatures combined with high RH cause rapid deterioration. During seed storage, seed moisture content and seed temperature together determine viability fall. Viability is measurable and this enables the most cost-effective store design to be determined for achievement of specified quality standards. For food grain, in-store temperatures and RH control moisture loss or gain. This is important financially (Agrawal *et al.,* 1984). In-store microclimate also affects the rate of increase of storage insects (WFP, 1983). Because no published method for predicting in-store conditions existed for tropical stores, ODNRI undertook the project as a contribution to the study of the effect of environment on stored produce, in particular the effect of climate and store design on seed packed in moisture vapour-proof sacks.

OBJECTIVE

The objective was to develop and verify a mathematical model of wide application capable of predicting the internal store climate inside selected warehouses and which was adaptable to varying parameters including different locations and climates, building size and orientation, roof pitch and varying ventilation.

PROGRAM DEVELOPMENT

It is often assumed by storage workers that produce stacked in store acquires the mean ambient temperature of the store. In the tropics, however, much heat is transferred through the store roof and walls from solar radiation and therefore the mean stack temperature normally will be above the mean ambient temperature. No basis for estimating daily variation of in-store temperature or in-stack temperatures has been available, because published equations for predicting temperatures in buildings (CIBS, 1979; Petherbridge 1974) assume that the buildings are occupied by people but empty of grain. For grain/seed stores which are empty of people but contain dry grain/seed, very little heat is produced (by dry grain) but considerable damping of temperature swings occurs. The heat transfer processes are:

- *radiation:* full sun and diffuse solar radiation falling on building surfaces is partly absorbed depending on the building's absorptivity and heat is conducted through the cladding at a rate determined by the intensity of radiation and the thermal properties of the building. These include the transmittance ('U' value) and the external and internal surface resistances.

- *long-wave radiation loss:* is considered for the roof of the building only; the emissivity of the surface replaces the absorptivity coefficient.
- *conduction:* occurs through the building materials and is dependent on their transmittances, i.e. on their thermal conductivity and thickness. This is also true of the outside layer of produce stacked in the store which absorbs and releases heat.
- *ventilation:* heat is transferred when the free air within the store is exchanged with ambient air.

For consideration of the 24-hour range or 'swing' in temperature, additional properties of the building components are involved, also the thermal capacity of the produce stacks. Appendix 1 gives details of these variables and predictive equations used for program verification - see below.

To apply the equations to a specific location, the climatic data, in particular solar radiation and related parameters, are required. Values are given in CIBS (1979) and a selection of representative values for tropical sites form the data-bank in the program (*see* Tables 1 and 2). The computer calculation of solar

Table 1

Radiation intensities (W/m^2) at different latitudes in arid regions

Latitude	Orientation	Daily mean	Increment at 1200h
5° *	N	237	403
	S	110	240
	E	228	188
	W	228	122
	Horizontal	353	817
20° **	N	158	158
	S	99	211
	E	238	72
	W	238	72
	Horizontal	398	826
35° **	N	132	174
	S	165	417
	E	203	103
	W	203	103
	Horizontal	407	799

Source:* Petherbridge (1974)
**Calculated for an arid climate. CIBS (1979) pp. A6-9.

Notes: Assumptions:
Period May 22 or July 23
Sky clarity factor = 1.2
Ground reflectance correction factor = 0.50
Orientation of long walls EW

Table 2

Radiation intensities (W/m^2) at latitude 5° in humid regions

Latitude	Orientation	24h mean	Increment at 1200 h
5° *	N	157	238
	S	51	104
	E	149	6
	W	149	6
	Horizontal	301	694

Source: *See* Table 1

Notes: Assumptions as for Table 1 except sky clarity factor = 1.0.

radiation is shown in Appendix 2. Data on building materials are also required; the data-bank includes selected wall and roof types (*see* Tables 3 and 4). The costs given are United Kingdom values but can be replaced if required. The calculation of 'U' values is shown in Appendix 3. The program employs psychometric equations to convert ambient RH to in-store RH, but does not take the effect of produce moisture on in-store RH into account. It is assumed that seed is packed in moisture-vapour-proof sacks and that therefore seed moisture content is not affected by the store atmosphere. Because seed moisture content is unchanging during storage, seed viability equations can

Table 3

Thermal properties and costs of four wall types

Property	Walls				
	Symbol	Rusty corrugated galvanized steel (0.6 mm)	Clean corrugated galvanized steel (0.6 mm)	Concrete blocks	Light weight concrete blocks
Surface resistance (m^2 °C W^{-1}	R_{so}	0.05	0.05	0.05	0.05
Absorpitivity coefficient	a	0.90	0.80	0.40	0.40
Transmittance (Wm^{-2} °C^{-1})	U	5.00	4.00	1.41	0.70
Decrement factor	f	1.00	1.00	0.43	0.28
Admittance (Wm^{-2} °C^{-1})	Y	5.00	4.00	6.00	3.50
Emissivity	e	NA	NA	NA	NA
Construction costs (£m^{-2})	—	(13.00)	13.00	23.40	30.30

Source: Thermal properties from, or calculated from, data provided by CIBS Guide A3 (1980) and Koenigsberger *et al.* (1973). United Kingdom material and labour costs from Spons (1987).

Table 4

Thermal properties and costs of four roof types*

Property symbol	Roofs			
	Rusty/dull corrugated galvanized steel (0.6 mm)	Clean/dull corrugated galvanized steel (0.6 mm)	Corrugated aluminium backed with 25 mm fibreboard	Corrugated and polished aluminium backed with 25 mm polyurethane foam
R_{so}	0.05	0.05	0.05	0.05
a	0.90	0.80	0.30	0.20
U	5.00	4.00	1.00	0.36
f	1.00	1.00	0.90	1.00
Y	5.00	4.00	1.00	3.00
e	0.90	0.80	0.30	0.20
£m^{-2}	(13.50)	13.50	34.00	48.50

Note: * *See* Table 3 for symbol description and the sources of this table.

be applied. Indeed for naturally ventilated seed stores the program employs viability equations (*see* Appendix 4) to predict one of the variables – seed moisture content, seed viability or seed storage period – given the other two. The seed temperature employed in this calculation is effective temperature (*see* Appendix 5) which allows for the above average viability loss caused by the higher storage temperatures over 24 hours. Effective temperatures of seed are distinct from environmental temperatures of the store which include radiant as well as dry bulb temperatures (*see* Appendix 1). Drying costs are discussed in Appendix 6.

The input of these data and the calculations performed by the mathematical model are shown graphically in the flow chart (*see* Figure 1). These operations result in a print-out of technical and economic data. A typical print-out is shown in Appendix 7. The print-out shows all parameters mentioned above (with the exception of solar radiation/local climate which is printed out as shown in Tables 1 and 2). These include the design features, stock data and ventilation rate which provide, through the model, the output of various temperatures and in-store RH shown. Finally the print-out gives building costs, dryer and seed data with drying costs.

PROGRAM VERIFICATION

As stated above, the mathematical model predicts the mean environmental temperature and temperature swing in-store (*see* Appendix 1) using modified heat balance equations. Partial verification of this model under limited conditions is described below. There was no seed packed in polyethylene lined bags available nor was there blustery weather. It was not possible to verify the viability equations nor to test the model for variable ventilation. However, the model's ability to predict temperatures for food grain packed in permeable sacks was able to be tested.

Test parameters

The tropical climate chosen for the trial was warm humid as defined by Koenigsberger, (1973) with latitude 6°N. The dry season in March-April was selected because calm periods with light and mainly unidirectional winds prevail. This meant that store ventilation would be reduced but steady. The stores chosen for the test had thermal properties representative of a range of typical commercial grain stores for bagged produce, but contained no seed in impermeable sacks. Different ventilation regimes were examined and diurnal changes in ambient/in-store temperatures and RH were measured.

Test implementation

Seven trials were completed over one month. The variables required to test the program and methods of measurement are described in Table 5 and Appendix 7. Preparation for these trials included choosing and testing measurement equipment. Since this had to be transported to Sri Lanka and then from site to site and store to store it needed to be robust but light. It also needed to be battery operated since not all sites had mains electricity. Pre-testing of equipment revealed several failures and therefore spares were carried of every item; this was justified because the solar integrator, the anemometer and the chart recorder broke down during the trials but could be replaced.

The data recorded by these instruments was analysed at once on site using the computer program on a small portable computer.

Test results – general

Figures 2-5 give store dimensions and dimensions of produce stacks. The stacks contained grain in permeable rather than impermeable sacks. Table 6 describes the various store designs with their ventilation regimes and the effect of climate on their in-store temperatures and temperature swings. The masonry

Figure 1
Flow chart

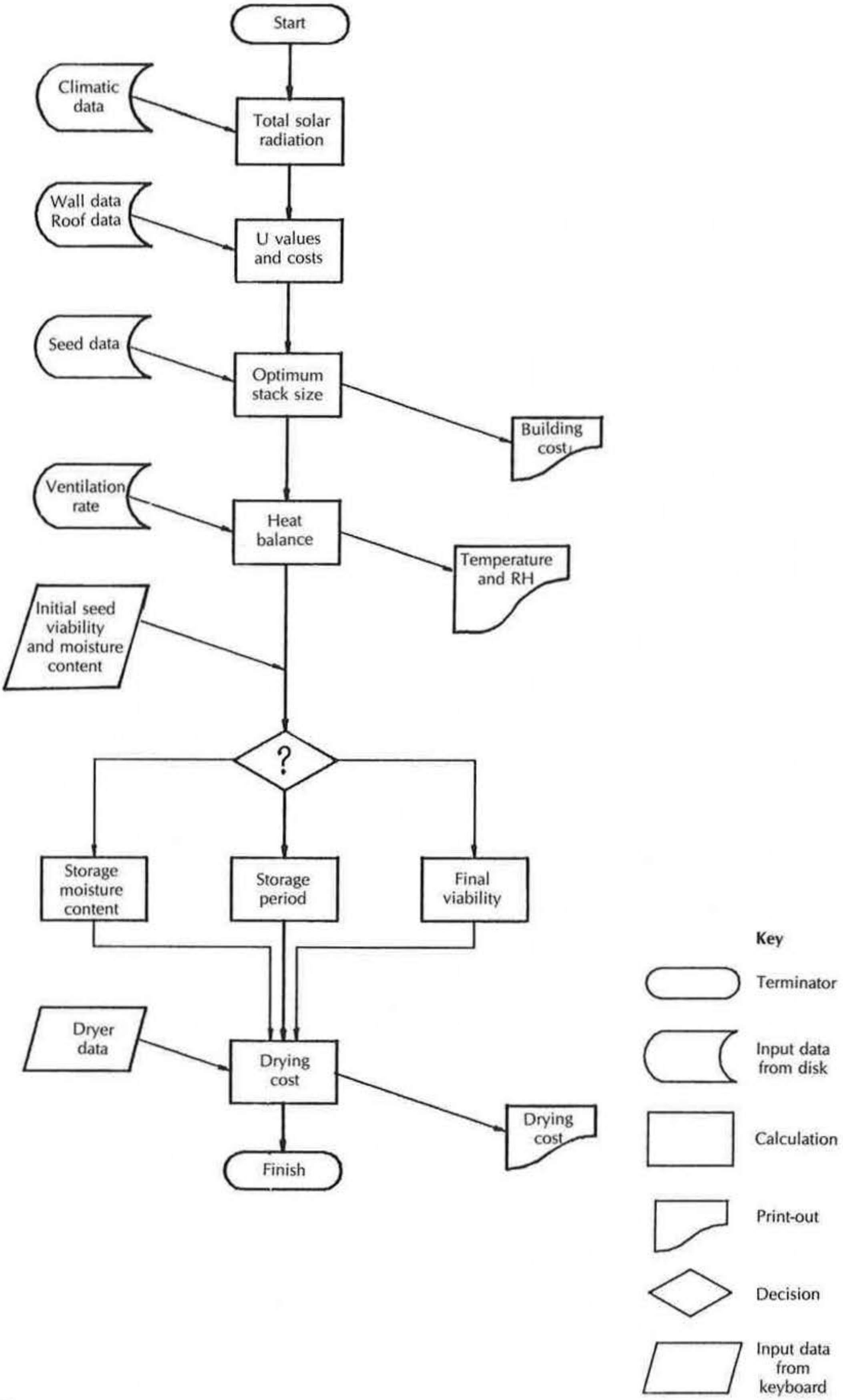


Table 5

Variables and methods of measurement

Category	Variable	Measurement
Climate	Ambient temperature	Thermohygraph in a Stevenson Screen and checks with Protimeter temperature sensor
	Solar radiation	Silicon diode solarimeter and chart recorder
	Wind speed	Sensitive anenometer and recorder
	Ambient RH	Thermohygraph in a Stevenson Screen and checks with whirling hygrometer
Building	Orientation	Compass
	Dimensions	Rules, tapes, ladders, etc.
	Transmittance	Reference A3, CIBS (1986)
	Absorptivity	BS4800 (1981) reflectance colour code
	Decrement	Site measurement and reference
	Surface resistance	Site measurement of wind speed
	Admittance	Reference A3, CIBS (1980)
	Emissivity	Reference A3, CIBS (1980)
In-store	Environmental temperature	From globe and screened thermometers and also thermocouples in stacks and recorder
	Air changes per hour	Includes the use of Squirrel data logger for recording air speeds with hot wire anenometers
	Specific heat	Measurement of moisture content and reference (Brooker *et al*, 1982)
	Time lag	Chart recording of stack temperature
	Relative humidity	Protimeter RH sensor plus whirling hydrometer and thermohydrographs

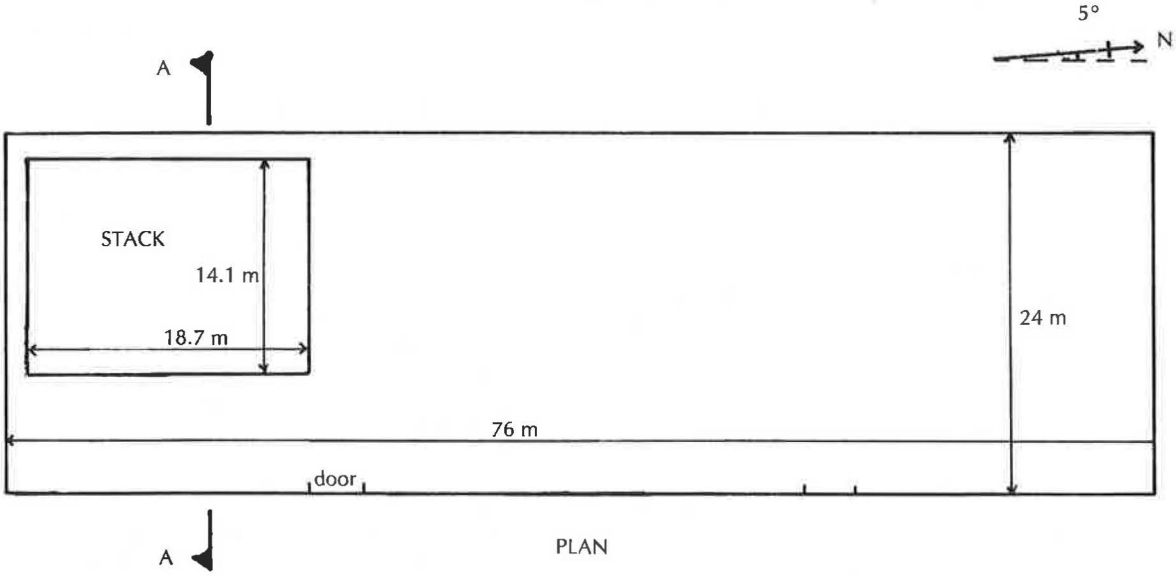
Table 6

Effect of environment and store design on in-store temperature and temperature swings (shown as (±))

Trial no.	Store design		Environment				Average in-store temperature (°C)
	Cladding type	Ventilation regime	Local weather	Average temperature (°C)	Natural ventilation (ach)	Average solar radiation (W/m^2)	
1	Masonry walls, asbestos roof	Ridge and eaves open	Warm and calm	28.5 (±3.5)	2.4	278	32.7 (±8.0)
2(a)	ditto	Infiltration only	Warm and calm	29.5 (±3.7)	0.4	264	34.0 (±5.6)
2(b)	ditto	ditto	Warm and calm	29.5 (±3.0)	0.4	264	34.6 (±4.4)
3	Lower walls masonry, upper walls steel, roof steel	Infiltration only	Warm and calm	29.4 (±4.5)	0.4	262	32.5 (±5.4)
4	ditto	Eaves open	Warm and calm	29.6 (±4.0)	2.8	258	33.0 (±6.3)
5	ditto	Doors open	Cloudy, very calm	29.7 (±4.5)	6.4	235	31.2 (±5.2)
6(a)	Walls and roof steel	Infiltration only	Warm and calm	30.5 (±3.0)	2.6	245	32.7 (±4.0)
6(b)	ditto	ditto	Warm and calm	30.5 (±3.0)	2.6	245	32.7 (±5.0)
7	ditto	Doors open	Very cloudy, calm	29.0 (±3.0)	5.1	191	31.2 (±4.3)

Note: The majority of stores were empty, but Trial 1, 100 t, Trials 2(a) and (b) 850 t, Trial 6, 1500 t bagged rice were included in the program.

Figure 2
Trial 1, detail of warehouse



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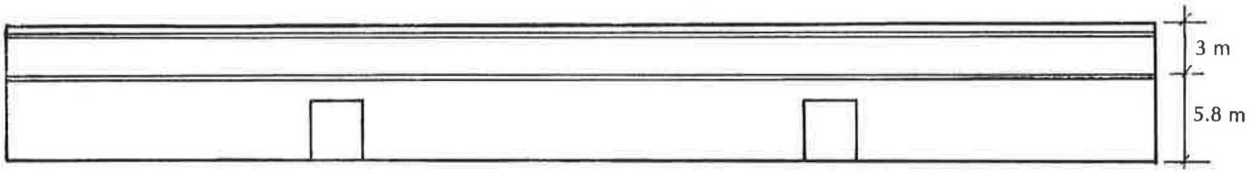
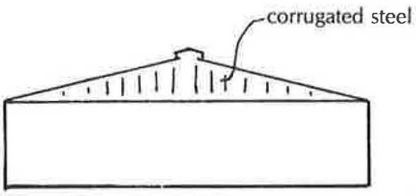


SIDE ELEVATION



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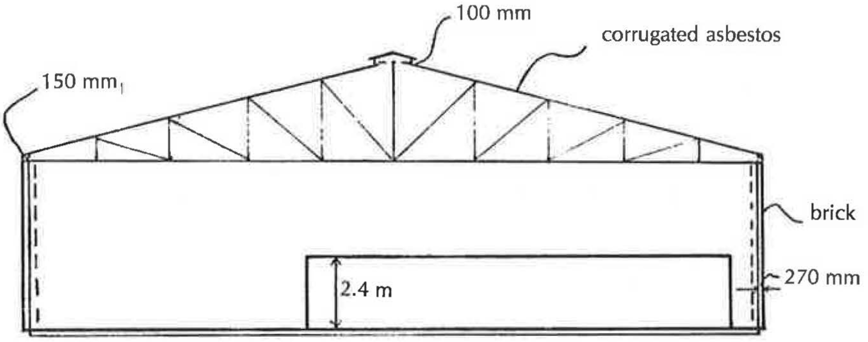
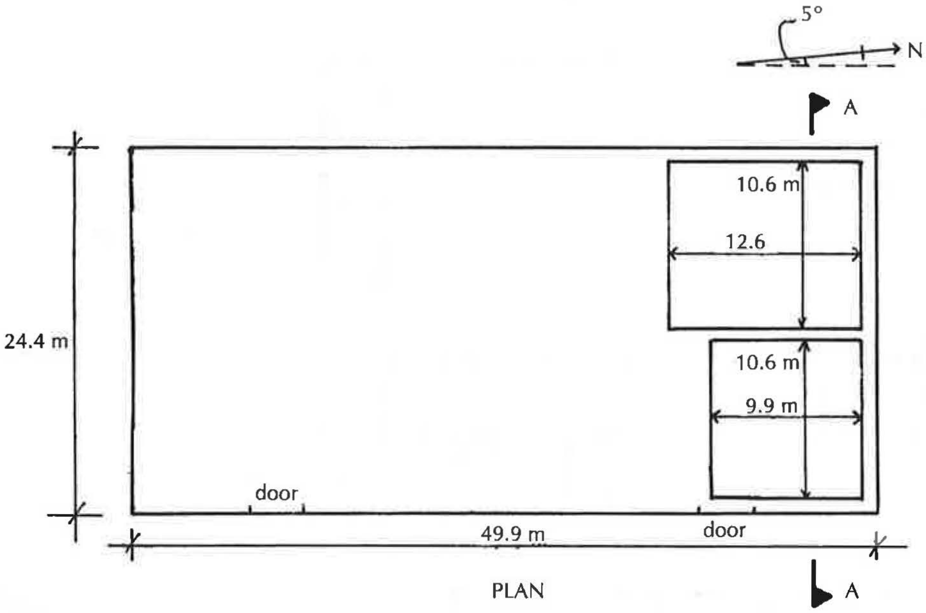


SECTION A-A

Figure 3
Trial 2, detail of warehouse



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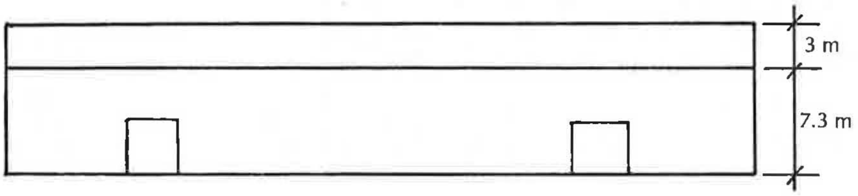

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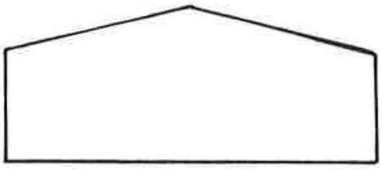

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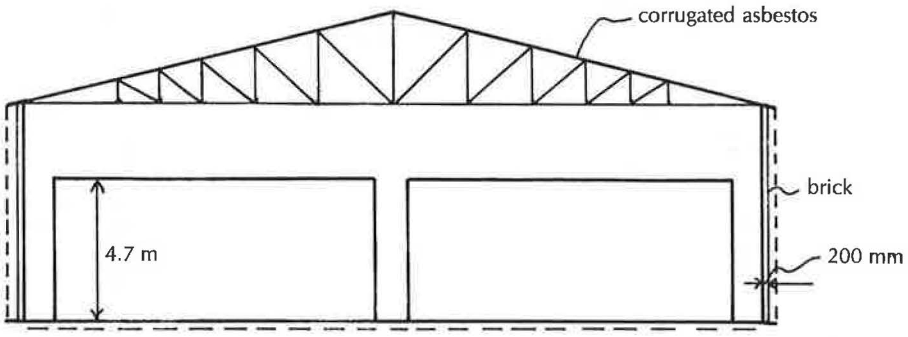
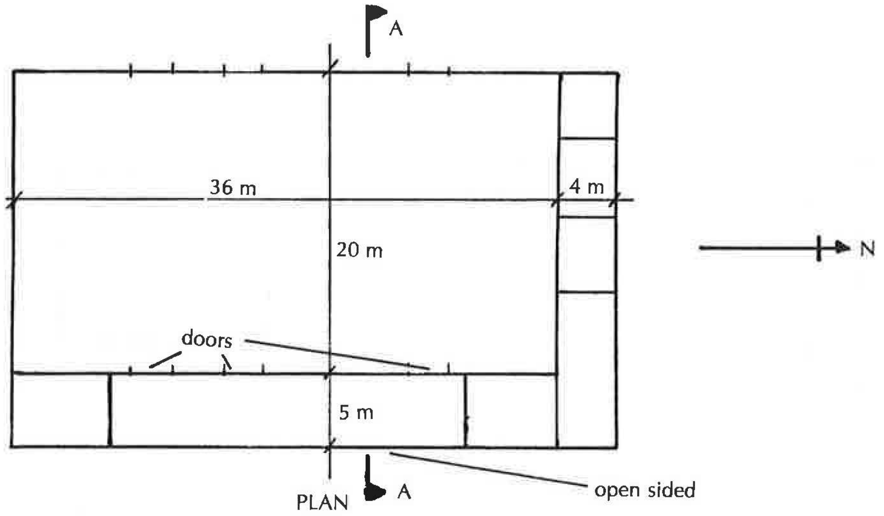


SECTION A-A

Figure 4
Trials 3, 4 and 5, detail of warehouse



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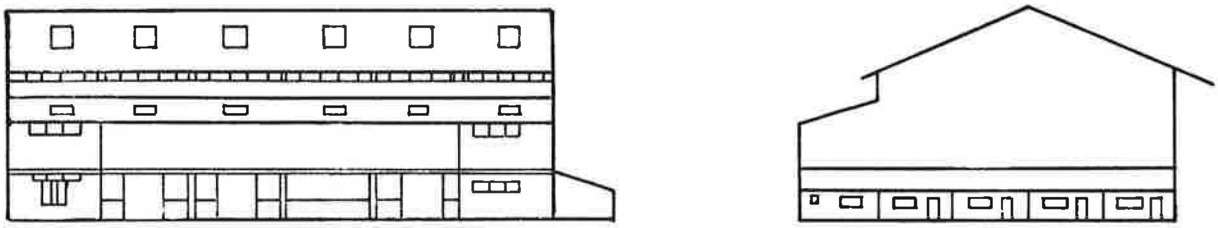
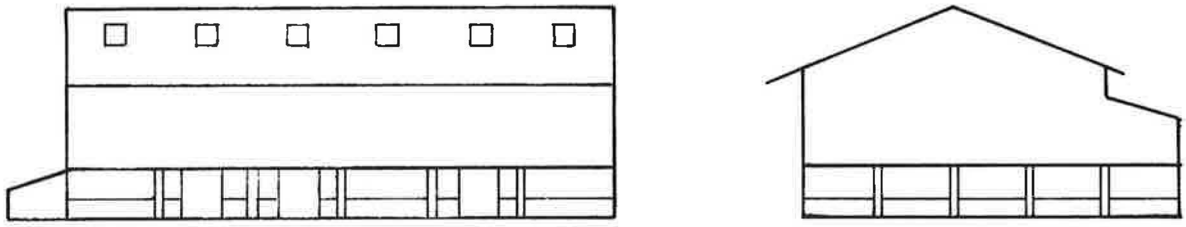


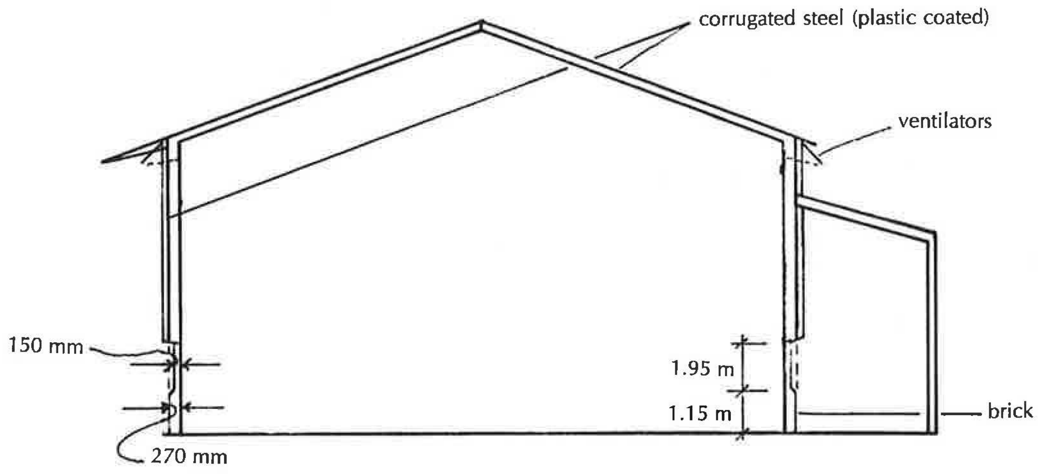
EAST ELEVATION

NORTH ELEVATION



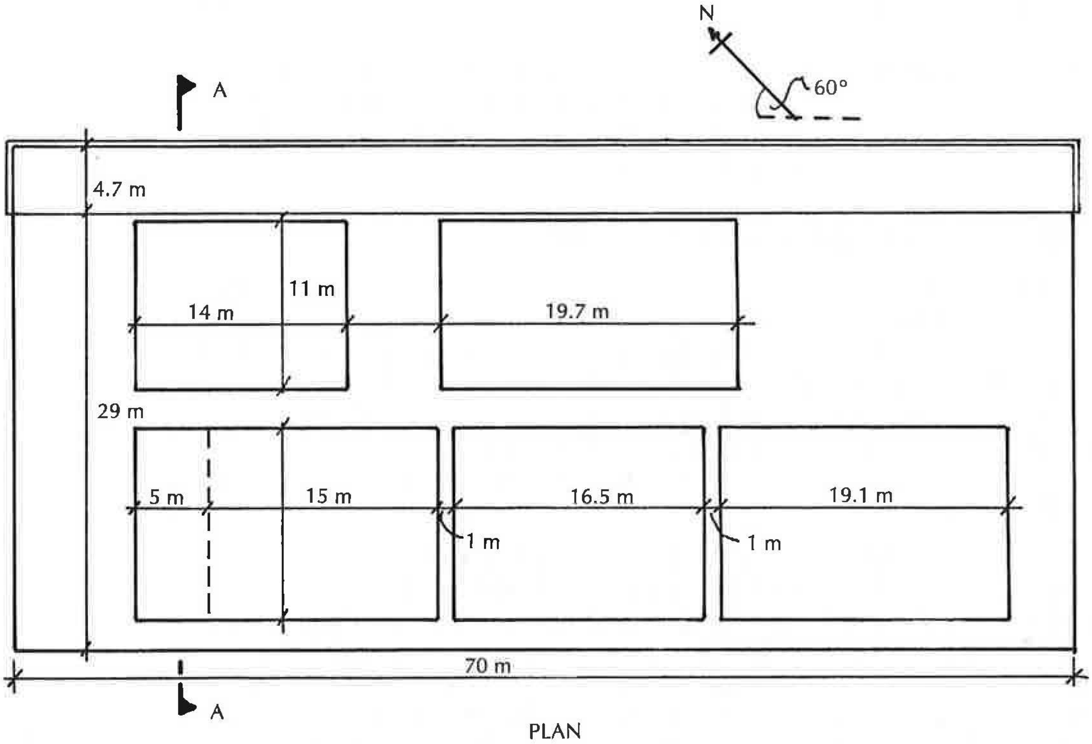
WEST ELEVATION

SOUTH ELEVATION



SECTION A-A

Figure 5
Trials 6 and 7, detail of warehouses



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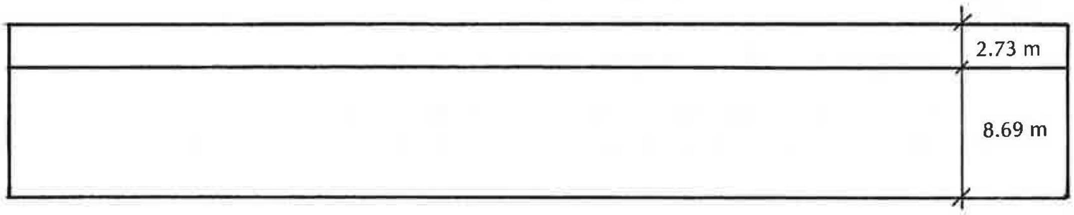
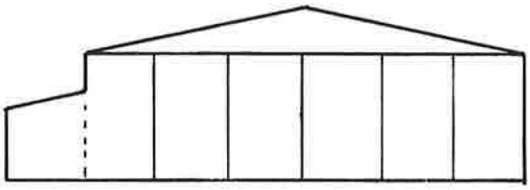


SIDE ELEVATION



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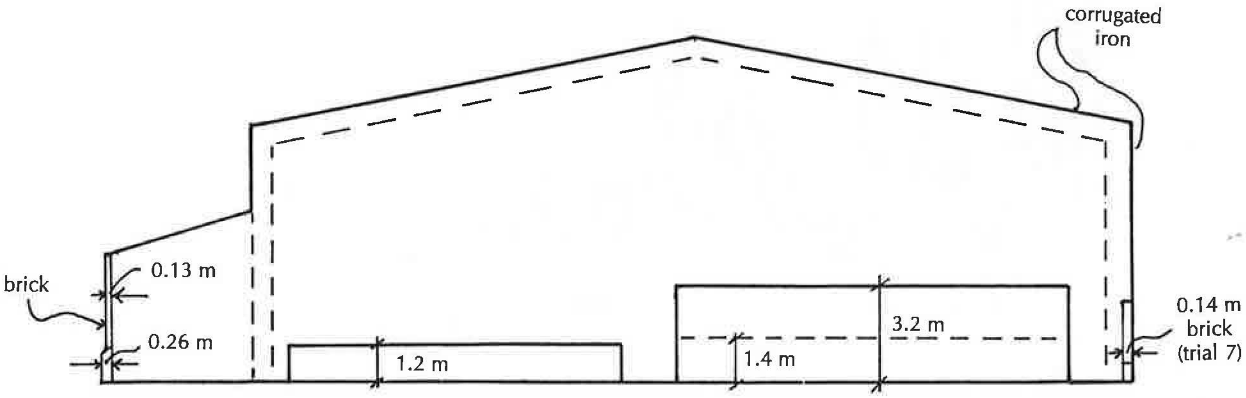


SECTION A-A

Note: Stacks only in trial 6

stores (trials 1 and 2) had darkened asbestos cement roof cladding with absorptivity estimated at 0.8 while the other stores all had bright reflective steel roofs with absorptivity estimated at 0.3 (trials 3-7). This factor reduced the thermal superiority of the masonry stores; high values of absorptivity increased the diurnal temperature swing as well as the average value. By contrast in trials 5, 6 and 7, cloud reduced solar radiation and this reduced temperatures in the thermally inferior stores. As a result, the maximum temperature difference between stores was only 3.4°C.

Test results – ventilation measurement

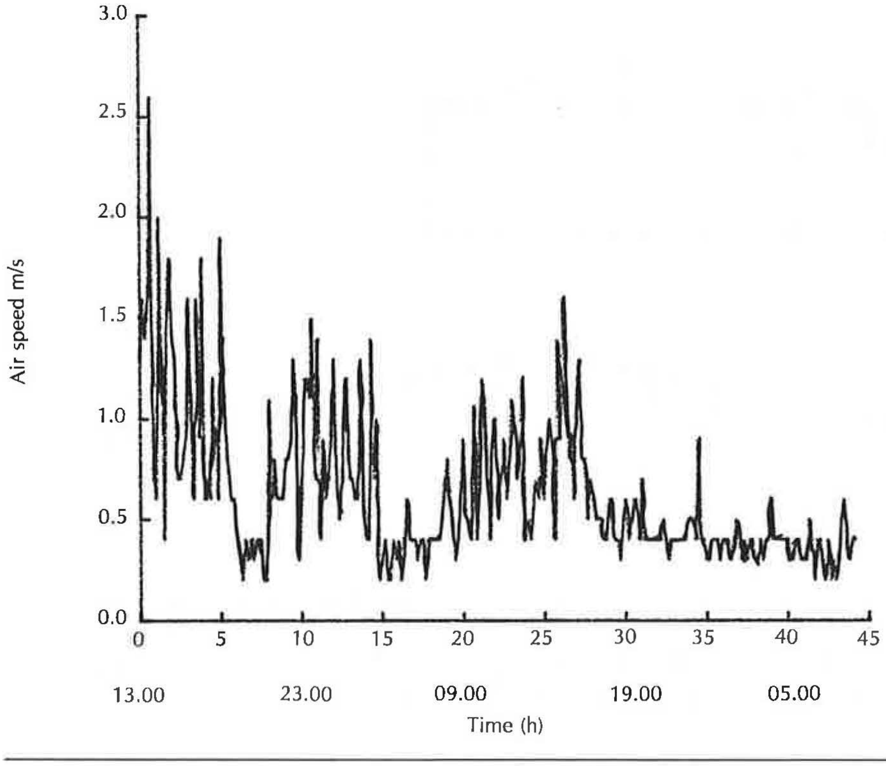
Because changes in wind direction were small and wind speeds were low, average in-store airspeeds could be measured with a hot-wire anemometer and recorded with a data logger (*see* Figure 6). The average air-speed at the door or ventilator yields the volume flow and hence the number of air changes per hour (a.c.h.). When stores had no obvious ventilation, infiltration rates were calculated from average wind speeds (CIBS, 1976; BRE 1978). These speeds were checked against local meteorological station data and on average, agreed within 20%.

The rates of ventilation and infiltration are shown in Table 6. Although not directly the concern of this bulletin it is interesting to note that even in very calm weather, 'satisfactory'* air changes in stores can be achieved if wide doors opposite each other are opened (trials 5 and 7). In constrast, eaves ventilation hindered by control flaps and/or roof overhang gives relatively poor rates of air change (trials 1 and 4) down to infiltration levels. These data were supported by smoke tests which showed store air mixing in trial 5 (*see* Figure 7) but little store air movement in trial 3 (*see* Figure 8).

Test results – ambient and in-store temperatures

In all trials, 'screened'** air temperatures in stores follow the same general pattern of the site temperature but exceed its value by as much as 10°C: for

Figure 6
Trial 7: average airspeed measured by hot-wire anenometer



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*4-5 a.c.h. and above can be termed satisfactory, see below in case studies.
**Screened from radiant heat.

Figure 7
Smoke test with doors open shows turbulence and mixing in trial 5

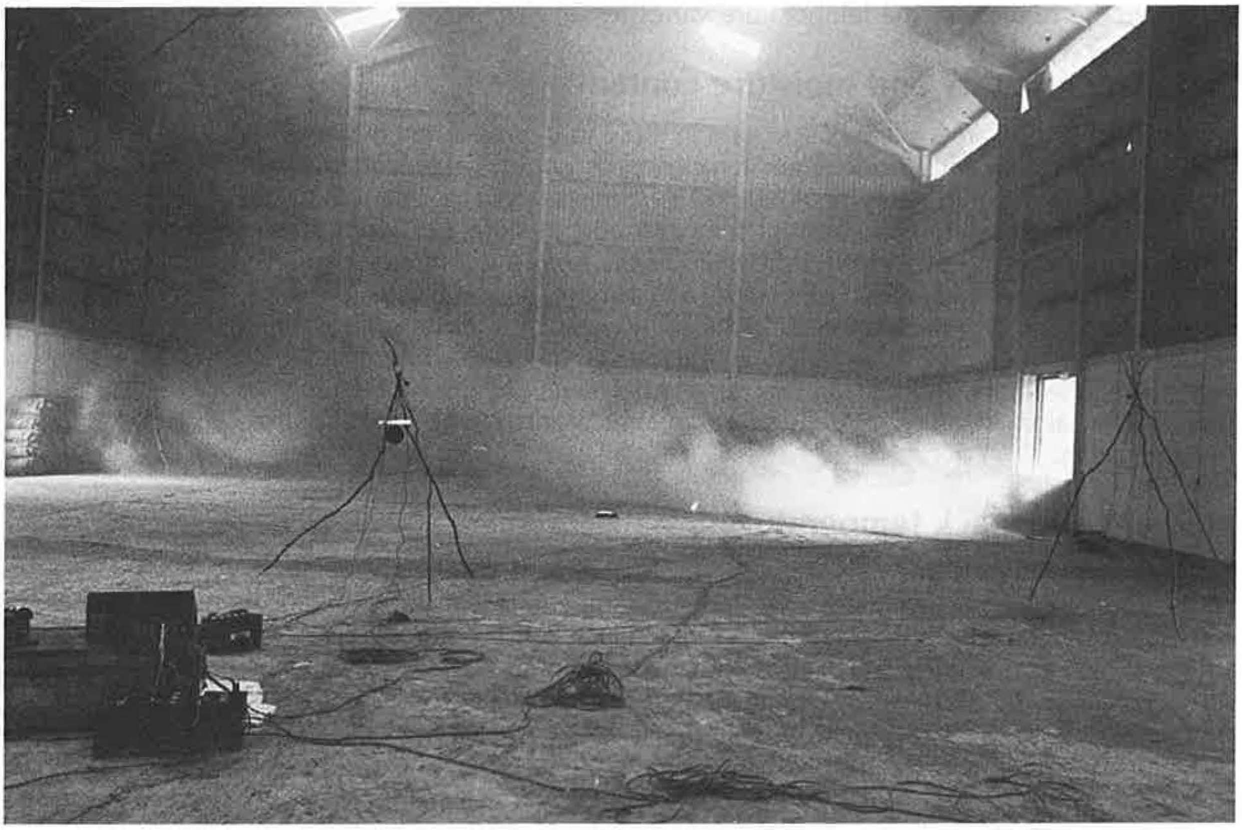
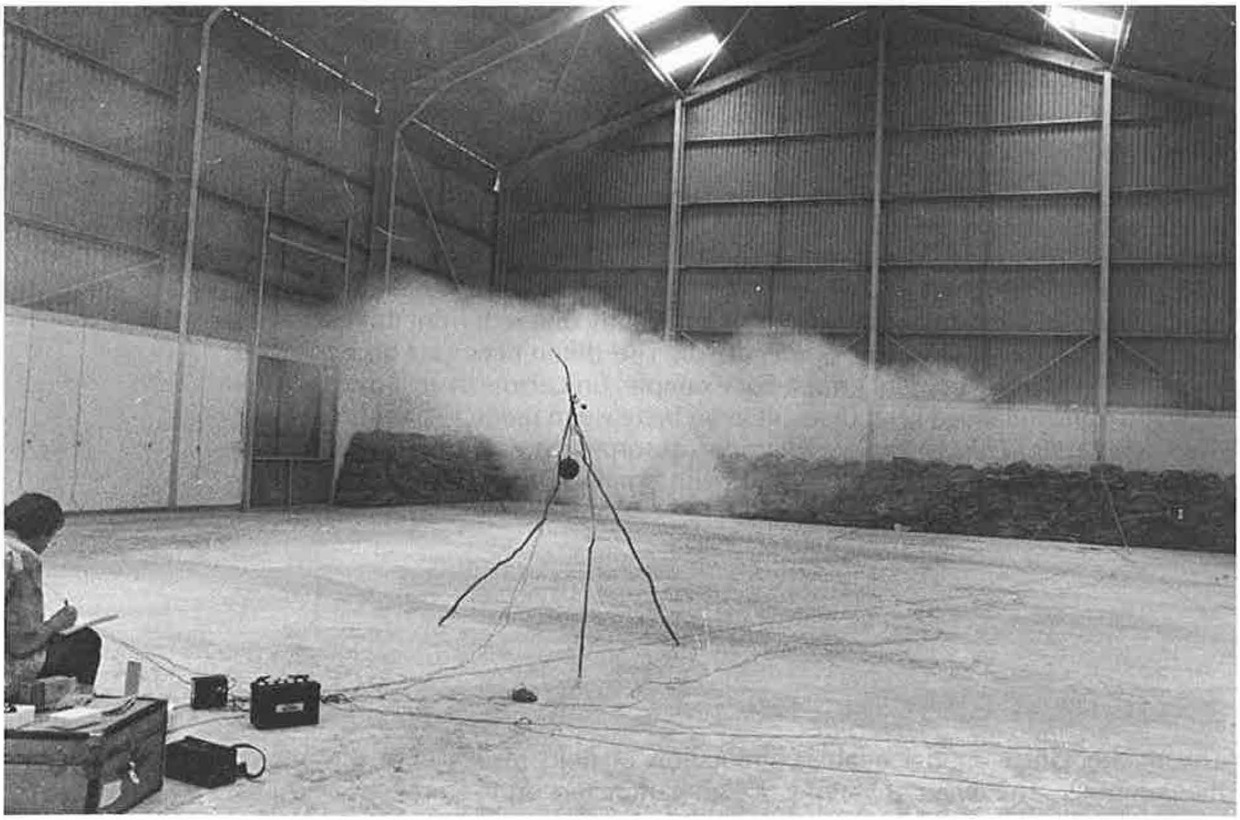


Figure 8
Smoke test with doors and ventilators closed shows little air movement of mixing in trial 3



example in Figure 9 the temperature at the centre of the warehouse is always higher than the site temperature and at peak times it is fully 10°C higher. Between the two stacks the temperature varies less.

Relative humidity and moisture content

As previously indicated, none of the grain in these trials was stored in moisture-vapour-proof sacks and while grain temperatures could be predicted, grain moisture content could not. Nonetheless it is interesting to note that influenced by the higher than ambient in-store temperatures, in-store RH were always lower than ambient RH and the difference varies from a minimum at midday to a maximum at or near dawn (*see* Figure 10). Where there is bagged produce, in-store RH near the stack appears to be influenced by the moisture content of the paddy. It is hoped to include this relationship in future work. Its absence does not affect the model's ability to predict seed/grain temperatures for permeable sacks, nor the model's more general predictive ability for impermeable sacks.

Radiant and stack temperatures

Radiant temperatures are necessary for the calculation of environmental or store temperature (*see* Appendix 1). Radiant temperatures in the stores were measured by black bulb thermometers and/or black ball thermocouples. In all trials, radiant temperature were highest near the roof and lowest near the store at floor level. In trials 3, 4, 5 and 7 with no produce in store, radiant temperatures varied as screened temperatures, but at a higher value: this was about 1°C except near the roof where it was 2-3°C higher.

Dry bulb temperatures close to stack surfaces and within stacks were measured using thermocouples and recorders. In trial 6 (*see* Figures 11 and 12) the stack surface temperature varied as the black bulb or radiant temperature, but in-stack temperatures on the top of the stack varied about the average value of 31°C by ± 2°C at 80mm depth. No variation was detectable at 150 mm depth. On the side of the stack there was no variation detectable at 60 mm depth.

Predicted temperatures

Table 7 presents the predicted in-store temperatures – calculated from the data described with the mathematical model – and the difference between these temperatures and the measured temperatures.

The largest difference between measured and predicted temperatures is 1.2°C. Also shown in the table are predicted temperature swings with differences from measured swings. The largest difference between measured and predicted temperature swings is 3.1°C. The predicted temperatures and temperature swings are not statistically significantly different from the measured temperatures and swings (*see* Appendix 8). The differences can be explained by cumulative measurement errors. For example, unit errors in absorptivity (0.8-0.9) and transmittance (4.0-5.0) result in an increase in predicted temperature of 1.4° ± 2.2°C. This is explained under absorptivity and transmittance (*see* Table 8). Similar errors could occur with small ventilation changes below 5 a.c.h. (see below).

PROGRAM CASE STUDIES

The mathematical model enables simulation of field results with the aid of the computer. The effect of varying design parameters on in-store temperatures can therefore be examined.

Figure 9
Trial 2: Ambient and in-store temperatures

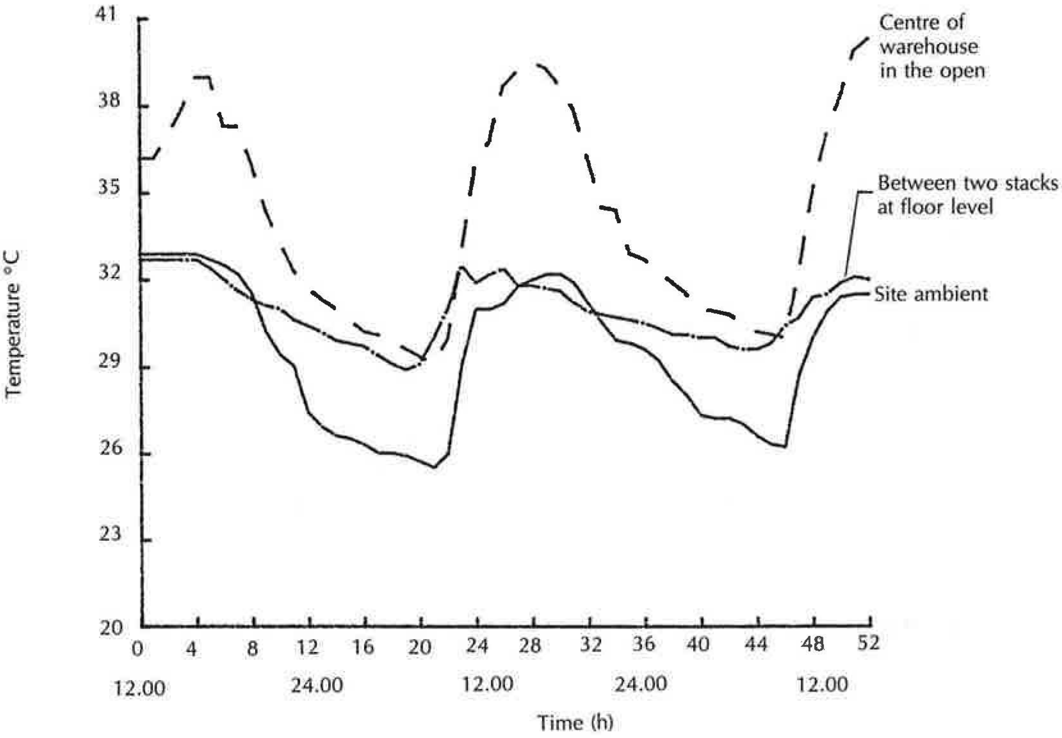


Figure 10
Trial 2: Ambient and in-store relative humidities

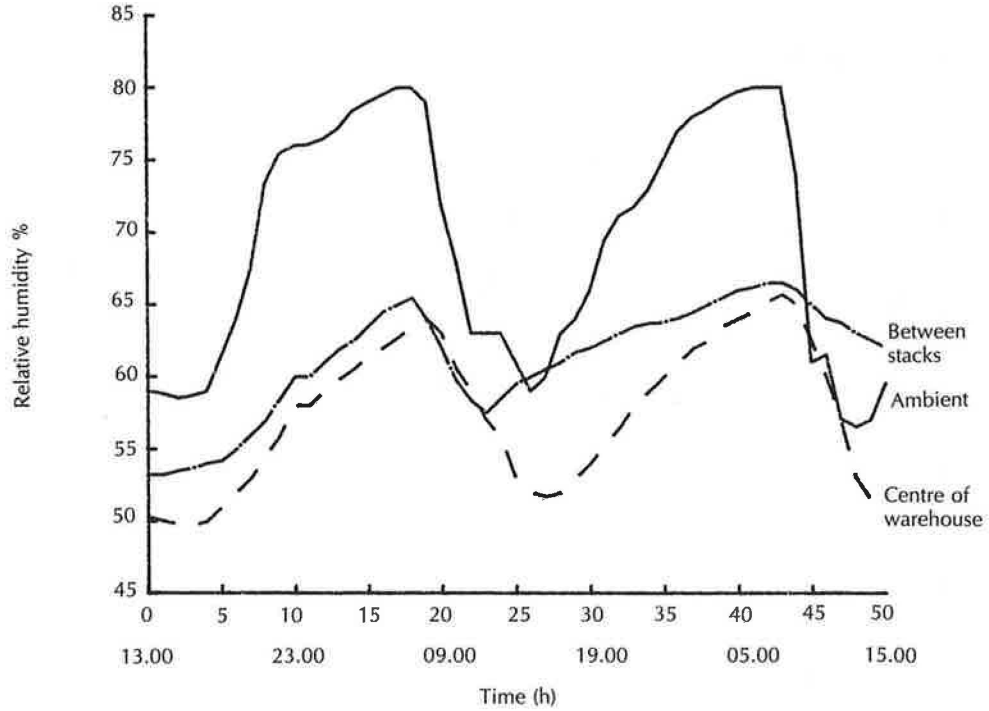
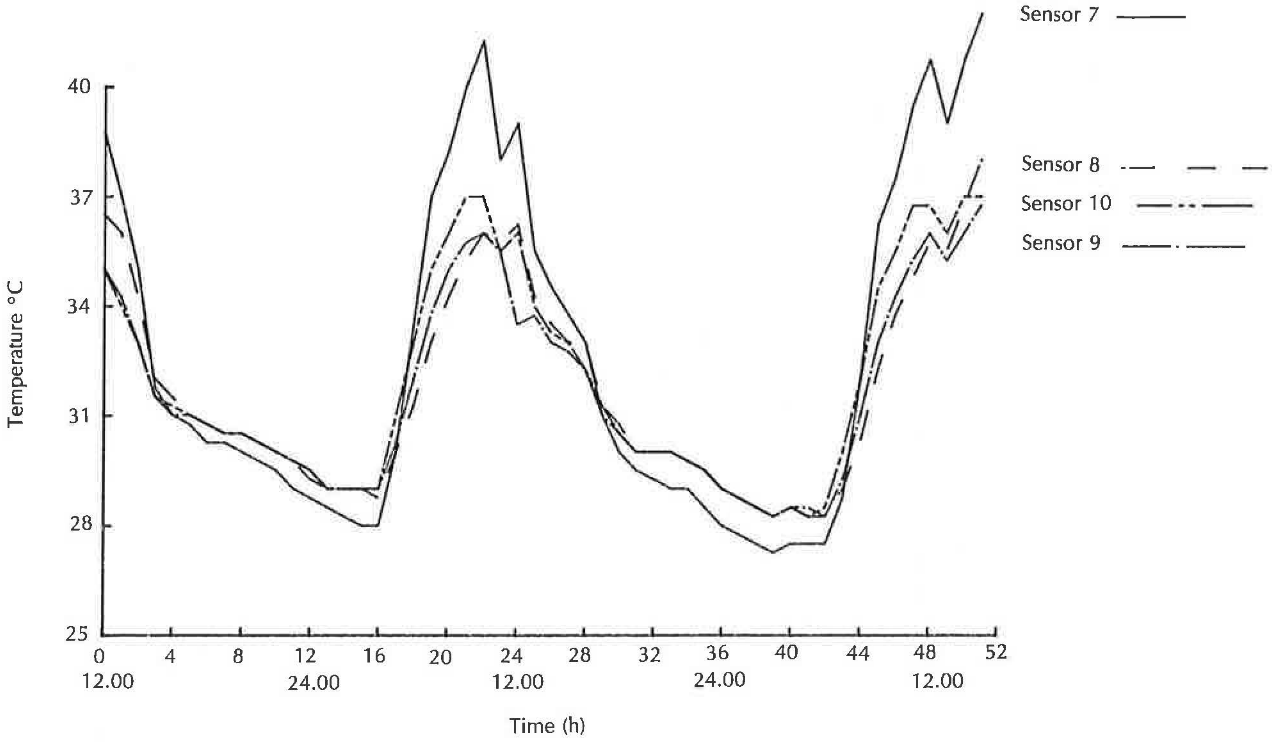


Figure 11
Trial 6: black bulb temperatures near stack



Position of sensors in stack

1 80 mm deep into SW face
2 30 mm deep into SW face
3 Surface on SW face
4 80 mm deep into top surface
5 30 mm deep into top surface
6 Surface on top face
7 Black bulb on top face
8 Black bulb on SW face (between stack and wall)
9 Black bulb on NW face (between stacks)
10 Black bulb on NE face (facing centre of store)

Figure 12
Trial 6: in-stack temperatures

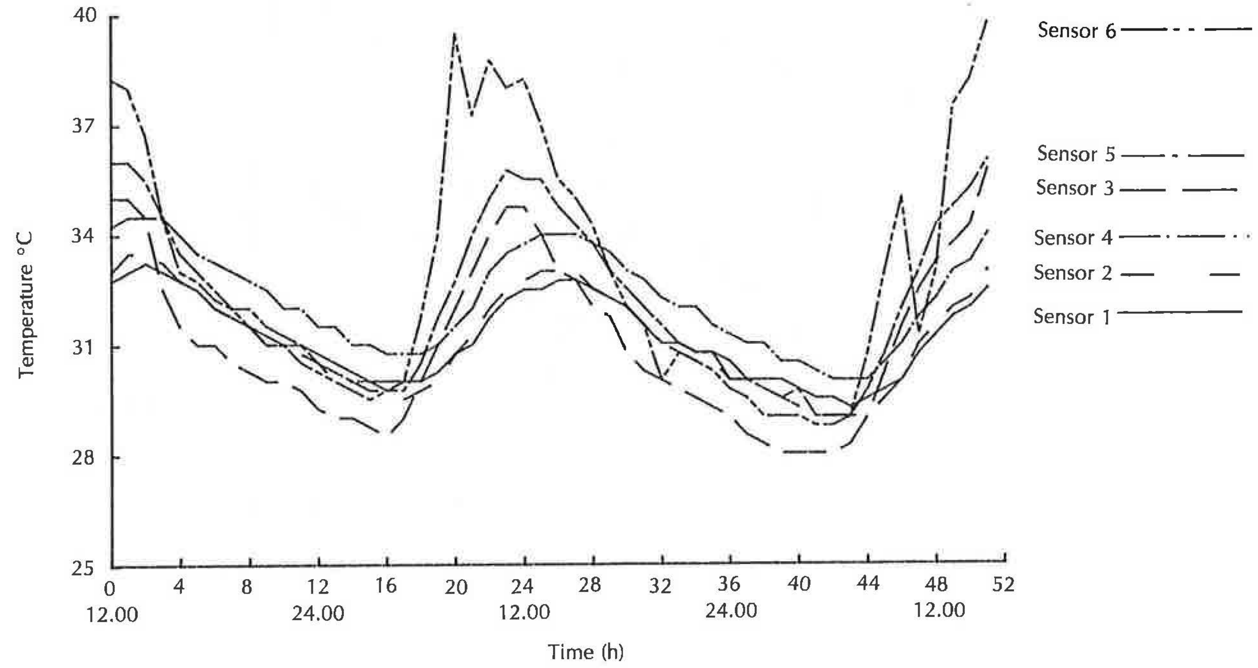


Table 7

Difference between predicted and measured temperature °C

Trial No.	1	2a	2b	3	4	5	6a	6b	7
Predicted	32.2	33.8	35.0	32.1	31.8	31.5	33.1	32.2	32.3
Measured	32.7	34.0	34.6	32.5	33.0	31.2	32.7	32.7	31.2
Difference	+0.5	+0.2	−0.4	+0.4	+1.2	−0.3	−0.4	+0.5	−1.1
Predicted swing	9.4	7.5	7.5	6.1	4.7	4.6	4.6	6.0	3.9
Measured swing	8.0	5.6	4.4	5.4	6.3	5.2	4.0	5.0	4.3
Difference	−1.4	−2.5	−3.1	−0.7	+1.6	+0.6	+0.6	−1.0	+0.4

Table 8

Effect of changes in thermal transmittance and absorptivity of cladding on in-store temperature and temperature swings

Thermal properties (units)	Wall and roof combinations			
	A Aluminium fibreboard roof, concrete block wall	B Clean, galvanized corrugated steel roof and wall	C Rusty, galvanized corrugated steel roof and wall	D Dirty, corrugated high alloy steel roof and wall
U (Wm^{-2} °C^{-1})	1.0 (1.4)	4.0	4.0	5.0
a (coefficient)	0.3 (0.4)	0.8	0.9	0.9
Average in-store temperature (°C)	31.2	34.6	35.3	36.0
(Swing °C)	(±1.5)	(±8.0)	(±8.9)	(±10.2)

Source: Tables 3 and 4

Notes These data apply to a store with dimensions 40 m × 15 m × 6 m to eaves. Roof pitch 17° orientation E-W in a humid climate (Table 2) and mean 24 h temperature of 30°C, swing ±6°C.
The store ventilation is a steady 5 a.c.h: this figure takes into account the store holding 1200 t of maize in five stacks.

Absorpivity

The effect of high absorptivity in roof cladding has been briefly described in test results above. Even a small increase in the value of this parameter will increase in-store temperature and temperature swing. Four combinations (A-D) of roof and wall cladding are shown in Table 8. When the cladding changes from clean steel (B) to rusty steel (C), absorptivity increases by 0.1 and in-store temperature by 0.7°C.

Transmittance

Table 8 also shows that a small increase in transmittance or U value increases store temperature and temperature swing by a similar amount (compare combination C with D). Conversely, if instead of steel cladding an aluminium fibreboard-backed roof and concrete block walls are employed (combination A) this will reduce absorptivity and transmittance considerably and cause in-store temperature and temperature swing to fall by 4.8°C and 8.7°C respectively.

Ventilation

Where absorptivity and transmittance influence store temperatures by 5°C or more, ventilation also has considerable effect as has been demonstrated in the field. Simulation with the ODNRI model (*see* Table 9) shows the effect on two designs. In the steel-clad store, increase in ventilation from 0.5 a.c.h. to 5 a.c.h. reduces store temperature by 2°C while there is a lesser effect in the aluminium/block clad store. Put another way, poorly insulated stores are very sensitive to the level of ventilation around the crucial 'calm' period when air changes per hour fall below 5 a.c.h. This frequently happens with natural ventilation in the tropics.

Table 9

Effect of ventilation on store temperature for two store designs

Ventilation rate, a.c.h.	0.5	1.0	2.0	3.0	5.0	10.0	25.0
Design and temperature, °C							
Rusty steel roof, clean steel walls	37.1	36.7	36.0	35.6	35.1*	34.5	34.0
Aluminium fibreboard-backed roof, concrete block walls	32.1	31.7	31.3	31.1	30.9*	30.7	30.6

Source: ODNRI computer program for a humid climate, Table 2; thermal properties, Tables 3 and 4; dimensions, Table 8.

Note: * Sample temperature swings for a ventilation rate of 5 a.c.h. are for the steel clad building ±8.7°C and for the aluminium roof with massive walls ±1.6°C.

Produce stack size

The effect of produce quantity and the number of stacks on swing temperatures is considerable; predicted temperature swing is reduced by having more produce in store and by increasing the number of stacks and therefore the surface area (*see* Tables 10a and 10b). The reduction of swing temperature is important because of its effect on seed (see below).

Table 10a

Effect of produce quantity on in-store temperature swings for a typical metal-clad store* in an arid climate

Quantity of produce stored** (t)	1200	700	100
Temperature swing °C	(±12.0)	(±13.7)	(±14.5)

Notes: * The cladding was rusty galvanized steel sheet (Tables 3 and 4) arid climate (Table 1). Ventilation rate in a.c.h. was calculated as follows:

Produce	*% Store volume*	*% Void volume×a.c.h. = Volume flow (equal)*
1200 t	37 V	63 V×5.00=3.15 V m^3/h
700 t	21 V	79 V×3.99=3.15 V m^3/h
100 t	3 V	97 V×3.24=3.15 V m^3/h

to ensure that the cooling effect of ventilation was comparable the model uses actual ventilation to calculate air changes per hour.

** Stored as 5 stacks each 11 m×6 m×5 m high for 1200 t;
1 stack 14 m×14 m×5 m high for 700 t, and
1 stack 10 m×5 m×3 m high 100 t.

Table 10b

Effect of stack size on in-store temperature swings, °C

	Mean	Swing °C
With a small number of large stacks (5 each 11 m×6 m×5 m)	39.5	±12.0
With a large number of small stacks (30 each 5 m×4 m×3 m)	39.5	±10.0
Difference	—	±2.0

Note: All parameters, *see* Table 10a and Table 8.

General

Massive walls with high admittance values reduce temperature swings. For example, in Table 9 the swing is reduced by over 7°C with concrete block walls. This is important for seed storage, see below.

The effect of doors and roof lights is to increase in-store temperatures by an amount depending on area and transmittance (*see* Table 11). Because store surface-area-to-volume ratio is larger in small stores these tend to be warmer (0.5°C) than large stores with the same parameters (*see* Table 12). Orientation, the model predicts, has a very small effect on in-store temperature (0.2°C) and none on temperature swing for a well-insulated building. For a poorly insulated building the effect on in-store temperature is greater, increasing from 38.5°C to 39.0°C from EW to NS. The temperature swing is reduced by 1.1°C (*see* Table 13). Finally, an increase of roof pitch from 17° to 30° has a very small effect (0.1°C) on in-store temperature (*see* Table 14).

Table 11

Effect of doors and roof lights on in-store temperature, °C

Cladding:	I	II	III	IV
Walls	Concrete block, no doors	Concrete block and 10% area steel doors	Concrete block, no doors	Concrete block and 10% area steel doors
Roof	Al/fibreboard, no roof lights	Al/fibreboard, no roof lights	Al/fibreboard, 10% area roof lights*	Al/fibreboard, 10% area roof lights*
In-store temperature (°C)	33.6	33.8	33.9	34.1
Cumulative difference °C		0.2	0.3	0.5

Notes: * Acrylic

These data obtain for an arid climate (*see* Table 1) at 5° latitude where ambient temperature is 32 ±6°C and ventilation 5 a.c.h. 1200 t of maize is stored in five equal stacks as before in a store 40 m×15 m×6 m high to eaves; roof pitch 20°.

Table 12

Contrast of in-store temperatures for a 150-tonne and 1200-tonne store

Size of store:			Difference
Tonnes	150	1200	
Dimensions (m)	20×7.5×3	40×15×6	
In-store temperature (°C)	34.1	33.6	0.5

Notes: Both stores are filled to 36% of total volume.
There is an arid climate (*see* Table 1) and the ventilation is equal (5 a.c.h.).

Table 13

Effect of orientation on in-store temperature

(a) Well-insulated building

Orientation:	E-W	N-S	Difference
In-store temperature °C	33.6	33.8	+0.2
(swing)	(±2.3)	(±2.3)	(−)

These data obtain for an arid climate (*see* Table 1) at 5° latitude where ambient temperature is 32 ±6°C combined with the effect of a well-insulated store with concrete block walls (*see* Table 3) and aluminium fibreboard-backed roof (*see* Table 4) and dimensions *see* Table 8).

1200 t of maize is stored in five equal stacks and constant ventilation is 5 a.c.h.

(b) Poorly insulated building

Orientation:	E-W	N-S	Difference
In-store temperature °C	38.5	39.0	+0.5
(swing)	(±11.7)	(±10.6)	(±1.1)

These data obtain for a poorly insulated building with rusty steel cladding (*see* Tables 3 and 4) with identical climate, ventilation and stocking rates as above.

Table 14

Effect of roof pitch on in-store climate

Roof pitch:	17°	30°
In-store average temperature °C	39.5	39.6
Swing (°C)	(±12.9)	(±13.3)
(RH %)	(37.0)	(36.9)

Note: Cladding rusty galvanized steel sheet: as in Table 10a the ventilation rate has been adjusted to give equal air exchange.

As already stated, during seed storage viability fall is determined by seed moisture content and seed temperature. This latter temperature, as explained on p. 6, is referred to as effective temperature. Effective temperature is higher than the average in-store temperature because it takes account of the extra viability fall caused by the high 'swing' temperature. Appendix 5 shows how this is calculated and the calculation is included in the computer program.

Effective temperatures are based on stacks being affected to 50 mm depth (*see* trial results above). Table 15 shows effective temperatures for different store types, together with the acceptable seed moisture content to meet specified criteria of viability. The example is calculated with the seed allowed to fall from 90% to 80% germination over 120 days. Building costs are generally a function of thermal properties: the thicker the wall the greater the insulation and admittance, and the higher the cost. Stores with the more costly roofs and walls have lower effective temperatures. With lower effective temperature the stored seed can now tolerate a higher acceptable moisture content, which in turn means lower drying costs (*see* Appendix 6).

Table 15

Effect of cladding on seed temperatures and moisture content with operational costs: the example of maize seed in a humid climate*

Cladding type		Effective temperature °C	Acceptable m.c.%	Annualized costs/tonne		
Wall	Roof			Building+ £	Drying= £	Total £
Rusty (galvanized) steel	Rusty steel	41.6	8.3	6.7	18.0	24.7
Rusty (galvanized) steel	Clean steel	38.8	8.9	6.7	14.0	20.7
Rusty (galvanized) steel	Aluminium fibreboard	34.1	10.2	6.7	6.6	14.0
Rusty (galvanized) steel	Aluminium polyurethane	33.8	10.3	7.8	6.5	14.3
Hollow concrete block	Rusty steel	39.5	8.8	7.1	12.0	19.1
Hollow concrete block	Clean steel	36.4	9.6	7.1	8.6	15.7
Hollow concrete block	Aluminium fibreboard	31.3	11.0	7.7	4.6	12.3 (optimum)
Hollow concrete block	Aluminium polyurethane	31.0	11.1	8.1	4.6	12.7
Light-weight concrete**	Rusty steel	40.4	8.5	7.3	14.0	21.3
Light-weight concrete	Clean steel	36.9	9.4	7.3	10.0	17.3
Light-weight concrete	Aluminium fibreboard	31.1	11.1	7.9	4.6	12.5
Light-weight concrete	Aluminium polyurethane	30.7	11.2	8.4	4.5	12.9

Sources: *See* previous tables.

Notes:

* 4 months storage in sealed polyethylene bags with no moisture loss or gain. Viability fall 90-80%. Annualized costs based on 1200 t annual throughput. Building prices based on Spons (1987) for cladding and a capital cost of £50 sterling per t for building floor and frame, both annualized at 10% interest over 20 years. For drying costs, *see* Appendix 6.

** Light-weight concrete provides better insulation than concrete blocks but has a lower admittance (*see* Table 3) and therefore when combined with steel roofing has higher effective temperatures than hollow concrete.

Table 15 shows effective temperatures and acceptable seed moisture contents for different store constructions, with related building and drying costs annualized at a 10% interest rate. When these costs are added the optimum cost may be selected. The combination of aluminium fibreboard-backed roof with concrete block walls results in a differential cost saving of up to £12.40 per tonne annually, based on United Kingdom costs.

Table 15 also highlights the disproportionate effect of roof insulation on effective temperature. A typical warehouse clad with rusty galvanized steel has an effective temperature of 42°C. When the walls of the warehouse are upgraded to hollow concrete blocks the effective temperature falls only 2°C to 40°C. But when the roof is upgraded to aluminium sheet with fibreboard backing the effective temperature falls 8°C to 34°C. (see discussion).

FUTURE WORK

The measurement of factors affecting seed temperature needs to be improved and has been made by the purchase of a carbon dioxide gas analyser for more accurate ventilation measurement (Carney and Dodd, 1986). This will be particularly important for verifying the model with variable ventilation. So far the model has been verified for lightly insulated buildings in a still humid climate and it is hoped to verify the model with a diversity of insulated buildings in a windy tropical climate, because then the program can be employed with more confidence. Until now, to keep the program short, constant ventilation, perfect mixing of store air and single value estimates of temperature have been assumed. The dry resultant temperature technique (CIBS, 1979) would allow these assumptions to be relaxed at the cost of simplicity. A commercial program employing this technique could be purchased to test its practical value for grain and seed storage. However, it is proposed to improve the current program's ability to predict changes in moisture content by linking it to a predictive model for heat and mass transfer in bag stacks. Further improvements have been suggested by Parkes (1987) involving the effect of severe cloud on the model and also the manner in which seed temperature fluctuates in bag stacks. Together, these improvements can enhance the practical value of the model. As has been shown, in its present form the model can reduce costs for seed storage with the optimum combination of store building design and drying regime.

DISCUSSION

The program highlights both the technical and economic importance of choosing a roof with low absorptivity and transmittance. The example of aluminium backed with wood fibre was chosen because its thermal properties were known. In the tropics any backing should be treated against insect attack and moisture ingress. Treated wood fibre and polyurethane may not be available or may be too expensive to import. In this case it is sensible to employ locally made insulation which has been shown to be resistant to insects and moisture ingress (Mayo, 1987).

The program obliges designers to assume values for ventilation rate and therefore draws attention to ventilation design and site climate, and to questions such as: will a sufficient ventilation rate be achieved with small eaves ventilators in calm weather? If only very low ventilation is possible, what will the effect be on effective temperature?

The program is a searching technique encouraging the user to test for sensitivity. For example, the appreciable difference between rusty and clean steel cladding was noted. The program also emphasizes the cumulative effect of poor ventilation, inadequate thermal properties and stock management on instore temperatures.

RECOMMENDATIONS

It is recommended that seed store designers should:

- choose roof cladding with low absorbtivity ($\leqslant 0.4$) and transmittance ($\leqslant 1.5$) but high admittance ($\geqslant 3.0$);
- ensure that large ventilators or doors on opposite sides of a suitably sited store can provide sufficient cooling in hot calm weather (5 a.c.h.);
- test the sensitivity of in-store temperatures to any assumptions made about climate, design or store managment by employing the ODNRI program* as a management aid.

CONCLUSIONS

The objectives of the project have been largely achieved: a model of wide application has been developed but it needs to be extended to cover moisture content prediction and to take account of cloud cover and temperature penetration of stacks. The model has been partially tested but needs further tests in windy conditions in the tropics with insulated buildings. The model has already been used to predict in-store conditions for design of uninsulated warehouses in Ethiopia, Kenya, Côte d'Ivoire, Liberia, Senegal, Sri Lanka and Tanzania.

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*It is hoped to make the program available in due course.

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Appendices

APPENDIX 1 PREDICTIVE EQUATIONS

The predictive equations relate environmental temperature in the store and in the produce as they are affected by temperature swings, climatic and thermal/building parameters and ventilation rate.

Environmental temperature $t_{ei} = (1/3)t_{ai} + (2/3)t_{ri}$

where t_{ai} = in-store air temperature °C measured with a screen thermometer

t_{ri} = mean radiant temperature °C measured with a black bulb thermometer

$$t_{ei} = t_{ao} + \frac{\sum AUR_{so}\,(aI_t - eI_L)}{\sum AU + C_v}$$

where

A = the area of each surface measured on site (includes vents + doors)

U = the transmittance, calculated measuring thickness of material on site

R_{so} = the surface resistance which is defined by measured wind speed

a = absorptivity/reflectance read on BS 4800 colour code

I_t = Av. 24 hr radiation measured with solarimeter

e = emissivity – related to *a* except for polished metal

I_L = long-wave radiation, applicable to roofs only ($e\,I_L$), taken as 50 W/m^2 (*see* Petherbridge, 1974)

C_v = ventilation coefficient $\frac{1}{C_v} = \frac{1}{0.33N\,(V - v)} + \frac{1}{4.8A}$

t_{ao} = ambient 24 h average temperature, average of maximum and minimum thermometer in shade

$$t_{ei}\ \text{swing} = \frac{\left(\sum fAU + C_v\right) t_{ao}\ \text{swing} + \sum fAUR_{so}\left(aI^1_t - eI_1\right)}{\sum AY + C_v + \frac{kK}{2w}}$$

Where

f = decrement value from CIBS guide A3 for each surface

t_{ao} = swing in ambient temperature (maximum and minimum recorded as above)

I^1_t = maximum increment of radiation on each surface – solarimeter records

Y = admittance value from CIBS guide for various materials

k = specific heat of grain at known moisture content

w = time lag for grain to reach maximum temperature

K = weight of produce affected by swing

N = air changes per hour

V = store volume, m^3

v = produce volume, m^3

Note: sol-air temperatures are not available for the tropics and therefore we use the expression above for environmental temperature, t_{ei}. This and other features of the equations are discussed elsewhere by O'Dowd and Dobie (1983).

The damping effect of the outer layers of grain (or seed) is calculated using the following data:

Bulk density of maize (depending on mc) = 750 kg/m^3
Depth of temperature penetration in stacks = 0.05 m
Specific heat of seed, from Brooker (1982) = 1788 J/kg°C
Time lag i.e. period required to absorb heat = 6 h

so that allowance for grain (or seed) in the denominator of the equation for

t^{ei} swing, is $$\frac{kK}{2W} = \frac{1}{2}\,\frac{\sum A \times 0.05 \times 750 \times 1788}{6 \times 60 \times 60} = 1.6 \sum A \qquad W/m^2\,°C$$

the equivalent of an admittance of 1.6.

Whether heat transfer is by diffusion which would allow admittance to be calculated using the CIBS (1980) method, is beyond the scope of this paper.

It can be said that this is a conservative estimate of Y because the response time from trials in Sri Lanka was nearer 3 h than 6 h.

APPENDIX 2 CLIMATE

The program can be used for any location any altitude and any time of year. The user feeds hourly values of direct and diffuse radiation from tables (CIBS 1979) into the computer which converts these into average total radiations and radiation swings using the equation:

$$I_t = K_a \;(I_v k_c) + I_d + 0.5\;(I_h k_v)$$

where I_t = total intensity W/m^2

I_v = vertical intensity W/m^2

I_h = horizontal intensity W/m^2

k_a = height correction

k_c = sky clarity correction

k_v = ground reflectance correction

Note: No correction for cloudy weather in the tropics is included here.

APPENDIX 3 CALCULATION OF U VALUES

The computer is programmed to calculate U values for any multi-layer wall or roof, where

$$U = \frac{1}{R_{so} + R_s i + R_a + R_1 + R_2 + \dots\dots\dots\dots + R_n}$$

R_{so} = surface resistance m^2 °C/W

R^{si} = internal surface resistance m^2 °C/W

R_a = airspace resistance m^2 °C/W

$$R_1 = \frac{d_1}{K_1}$$

d = layer thickness

K_1 = thermal conductivity W/m°C

The operator's guide provides a wide range of quantitative values.

APPENDIX 4 SEED VIABILITY EQUATIONS

Values for constants K_E, C_W, C_H and C_Q are fed into the program for cereals, cowpeas, chickpeas and soyabeans: (Ellis and Roberts, 1980)

$$V=K_i-p\quad 10\left(K_E-C_H\log m-C_Ht-C_Qt^2\right)$$

V and K_i are respectively final and initial viabilities (probit) *see* Roberts (1973). The equations give the required moisture *m* for any storage life *p*. The effective temperature is defined in Appendix 5.

APPENDIX 5 EFFECTIVE SEED TEMPERATURE

Seed temperatures in naturally ventilated stores vary diurnally; the arithmetic mean is not the effective temperature because the relationship between seed longevity and seed temperature is not linear (*see* Appendix 4). High temperatures have a disproportionately large effect. The programme computes T_e automatically

$$T_e=(\log(\text{antilog }(C_H\, t_{ei}\max)+\text{antilog }(C_H\, t_{ei}\min)/2)/C_H$$

where

t_{ei} max is the maximum in-store temperature

t_{ei} min is the minimum in-store temperature

C_H constant, *see* Appendix 4.

Source: Roberts (1973).

APPENDIX 6 DRYING COSTS

Drying costs vary with moisture extraction and range from a minimum of £4.50/t to £18.00/t per annum. These indicative figures are similar to a range of United Kingdom figures for 1987 (Barrett, 1988). The costs give some indication, along with United Kingdom contractors' costs, of seedsmen's options (*see* Table 15) for minimizing total costs/annum. Both drying and cladding costs will vary for every country, and the optimum combination for least-cost will be unique.

Calculation of drying costs is as follows. Dryer performance for the full range of moisture extraction is required, expressed in t/h. If variable costs and fixed costs are also known a combined annualized cost, including interest, can be calculated by the program. The basis for the drying costs shown in Table 15 includes 'fixed' cost element which does vary if different through-puts are experienced and a minimum drying period of 500 h is available.

Calculation of dryer performance

Say the dryer is rated at 5 t/h. Using a single layer bed theory as a first approximation

$$\text{MC ratio}=\frac{\text{Final m.c.}-\text{equilibrium m.c.}}{\text{Initial m.c.}-\text{equilibrium m.c.}}$$

where these are measured in dry basis. Therefore for an intake of 20% w.b. and final m.c. 15%, equilibrium m.c. at 44°C and 27% RH=7.5% m.c. d.b. for rice by extrapolation (Cromarty, 1982)

$$\text{MCR}=\frac{17.6-7.5}{25-7.5}=0.577$$

using the exponential expression

$\text{Log}_{10}(\text{MCR})=-0.1\ t$

t=2.4 h for 12 tonnes= t/h

Example:

Storage w.b.	m.c.% d.b.	MCR*	Drying* time h	Performance* t/h
8	8.7	0.07	11.6	1.0
9	9.9	0.14	8.6	1.4
10	11.1	0.21	6.8	1.8
11	12.3	0.27	5.6	2.1
12	13.6	0.35	4.6	2.6
13	15.0	0.43	3.7	3.2
14	16.3	0.50	2.9	4.1
15	17.6	0.57	2.4	5.0

Drying costs in Table 15 are a combination of operating costs (£5/h) and annualized capital costs based on £12,000 per dryer over 10 years at 10% interest. The 500 h drying period can necessitate use of more than one dryer.

Note: *Derived using expression above.

APPENDIX 7 PRINT-OUT

Walls: concrete block
Roof: aluminium

Length : 40 m
Breadth : 15 m
Height : 6 m
Roof angle : 20°
Long axis : EW
Floor admittance : 6

	Wall	Roof
Resistance (R)	0.06	00.044
Absorption (a)	0.4	0.3
Transmittance (U)	1.41	1
Decrement (f, g)	0.43	0.9
Admittance (b, h)	6	1
Emissivity (e)	—	0.3
Cost/sq. m	23.36	
Construction	concrete block	aluminium

1200 t maize stored (=36% of store volume)
5 stacks, each 11 m×6 m×5 m high
Assuming stacks affected to .05 m depth by store conditions

5 Air changes/h (d=.64)

T_{ei} minimum: 29.5 T_{ei}: 31.1°C (average in-store temperature °C)
T_{ei} maximum: 32.7 R_{hei}: 70.4°C (average in-store %RH)
T_e: 31.3°C

Building

Annualized cost	£2200/year £1.82/t/year with one intake (10% interest and 20 years life)

Dryers

Dryer type/make	batch
Rated throughput per dryer	3.7 t/hour
Purchase price per dryer	3000
Annualized cost per dryer	488.2/year (10% interest and 10 years' life)
Running cost per dryer	5/hour

Initial moisture content %	Initial probit	Final probit	Storage moisture content %	Life (days)	Dryers (no)	Drying costs £/t				
						Annual	Operating/ t	Operating/ year	Total/ year	Total/ t
15	1.64	0.84	11	120	2	980	1.4	1600	2600	2.2

Key to thermal properties for wall and roof cladding

Resistance (R) normally referred to as the external surface resistance R_{so} which varies with the degree of exposure from 0.02 $m^2 kW^{-1}$ for a severely exposed roof to 0.08 for a sheltered wall (CIBS, 1979).

Absorption (a) which is the absorbtivity coefficient or the proportion of heat absorbed by the surface.

Transmittance (U) depending on thermal conductivity and thickness.

Decrement (f, g) which allows for the damping effect on retransmitted energy (*see* admittance below).

Admittance (b, h) gives a measure of the ability of a building component to store and release energy over the daily cycle.

Emissivity (e) replaces the absorption coefficient for roofs for long wave radiation.

APPENDIX 8 STUDENTS' 't' TEST

Variates difference in store temperature °C		Differences in swings °C
+0.5	measured − predicted	−1.4
+0.2		−2.5
−0.4		−3.1
+0.4		−0.7
+1.2		+1.6
−0.3		+0.6
−0.4		−0.6
+0.5		−0.6
−1.1		+0.4
$\bar{x} = 0.0067°C$		$\bar{x} = 0.74°C$

$$S^2 = \sum X^2 - x^2$$

$$= \frac{3.77}{9} - x^2$$

$$= 0.414389$$

$$t = \frac{0.0667 / 8}{0.64373}$$

$$= 0.2931$$

This value of t will be exceeded by chance only once in four trials.

$$S^2 = \frac{22.75}{9} - (0.74)^2$$

$$= 2.2019592$$

$$S = 1.4839$$

$$t = \frac{0.74\sqrt{8}}{1.4839}$$

$$= 1.4105$$

This value of t will be exceeded by chance only once in ten trials.

Both differences are NOT significant at the 25% and 10% levels respectively. *See* Moroney (1956) and Howatson *et al.* (1972).

(2781/88) Hobbs the Printers of Southampton