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DRYING AND STORAGE OF OILSEED RAPE IN THE UK

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DRYING AND STORAGE OF OILSEED RAPE IN THE UK

PART I: PHYSICAL AND ENGINEERING ASPECTS

by

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PREFACE

Over the past two decades it has been the European Community's policy to encourage the production of temperate zone oilseeds, such as oilseed rape and sunflower, within the EC so as to generate an indigenous supply of vegetable oils and protein. As a consequence, the production of oilseed rape within the United Kingdom has expanded dramatically to over a million tonnes per annum. Growers, traders and users have had to learn not only how to grow this relatively "new" crop but also how to dry and store it.

The Authority's Oilseeds Research and Development Advisory Committee realised that growers, storekeepers and traders were handling this crop against a background of lack of technical advice on how best to dry and store it. With this in mind the Committee commissioned two literature reviews. One has been prepared by the Silsoe Research Institute on the physical and engineering aspects, particularly of drying, and the other has been prepared by the Ministry of Agriculture's Central Science Laboratory, particularly on pest control in the stored crop.

Both literature reviews have necessarily drawn heavily on the scientific literature in countries such as Canada and France where there is longer experience of this crop and where there has been more scientific investigation of the problems of drying, storing and pest control.

The reviews provide an up to date compendium of the current state of knowledge on these matters.

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NOTATION

Upper case

A_1 - A_3	coefficients of Equation 2.6
A	coefficient used in Equations 3.22 - 3.24, 3.30 and 3.31 - 3.32
B	" " " " 3.22, 3.30, 3.31 and 3.33
C	" " " " 3.23
D	" " " " 3.23
D_{av}	average diameter of seed, m
E_c	mass percentage of chaff in seed sample
E_f	mass percentage of fines in seed sample
E_s	mass percentage of clean seed in seed sample
G	germination, decimal
M	moisture content on a dry basis, fraction
M_o	initial moisture content on a dry basis, fraction
M_e	equilibrium moisture content on a dry basis, fraction
P_s	saturation vapour pressure, g/cm^2
ΔP	pressure drop per unit depth of bed, Pa/m
Q	airflow per unit height of radial flow bin, $m^3/(s\ m)$
R_m	moisture ratio, = $(M - M_e)/(M_o - M_e)$
S	wet mass of single seed, kg
T	temperature, °C
V	volume of single seed, m^3
W	moisture content on a wet basis, %
X	standardised normal deviate, = $(t - \bar{t})/\sigma$
X_o	value of X at t = o

Lower case

a	coefficient in equations 3.28 - 3.29, 3.32 and 3.42
a_1 - a_3	coefficients in Modifield Henderson equation 2.17
b	coefficient in equations 3.28 - 3.29, 3.33 and 3.42
b_1 - b_3	coefficient in Chung-Pfost equation 2.18
c_1 - c_3	coefficient in modified Halsey equation 2.19
c_p	specific heat at constant pressure, J/(kg K)
d_1 - d_3	coefficient in modified Oswin equation 2.20
h	surface heat transfer coefficient, $W/(m^2\ K)$
k	drying coefficient, min^{-1}
m	mass of dry matter, kg
n	coefficient in equation 3.18
p_1, p_2	coefficients in G.A.B. equation 2.21
q	coefficient of equation 3.26, Pa/m
r	coefficient of correlation

r_i, r_o	inner and outer radii respectively of ventilated part of radial bin
t	time, min
$\bar{t}$	half life of seed sample,min
v	air superficial velocity, m/s
w	mass of wet material, kg
x_1 - x_3	coefficients of equation 3.24

Greek symbols

α	thermal diffusivity, m^2/s
Δ_a	latent heat of vaporisation of water from seed, J/kg
Δ_f	" of free water, J/kg
ϵ	porosity decimal
λ	thermal conductivity, W/(m K)
μ	air dynamic viscosity, Pa s
ϕ	relative humidity, decimal
θ	maximum safe storage time, days
ρ_b, ρ_s	bulk and solid density respectively, kg/m^3
σ	standard deviation of distribution of seed death, min/probit unit

DRYING AND STORAGE OF OILSEED RAPE IN THE UK

PART I. PHYSICAL AND ENGINEERING ASPECTS

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1. Introduction

In compiling this review, the objective has been to distil, from the world scientific literature on the drying and storage of oilseed rape, the information necessary firstly to make recommendations on current practice and secondly to identify those areas in which further research may be required.

It is more than twenty years since oilseed rape was first introduced to UK agriculture as a viable alternative combinable crop. Over that period there has been a steady increase in the importance of the crop and a most significant shift from the original high erucic acid varieties to the 'double low' types which contain very little erucic acid and much lower quantities of glucosinolates. There has also been a considerable amount of research into the crop worldwide, if not so much within the UK. It was the knowledge that this research had not been properly scanned and put to the use of the UK grower, which inspired this review.

This part, Part 1, of the review is concerned with the engineering aspects of drying and storage while Part 2 deals with Pest Control. However, Part 1 does not deal only with the physical aspects of drying and storage. Insofar as the biological properties of the seed impinge upon, or dictate, engineering practice, they are reviewed also. Inevitably, there is a degree of overlap with Part 2 but this does not constitute duplication since the engineer's approach to the use of biological data is somewhat different to that of the biologist.

Not all of the references cited in the text are specific to rapeseed. They have relevance as examples of approach or technique. Conversely not all those papers found and dealing specifically with rapeseed are cited in the text. This is usually because they have added very little to the quantitative analysis of the various topics covered. These papers are listed separately. Articles in the popular press were not scanned because, although they often contain useful information, this is seldom rigorously substantiated scientifically. We took particular note of known problem areas in rapeseed drying and storage on which we found little or no research literature. Many references originated in Canada where work on 'Canola', the Canadian term for 'double low' varieties, has helped establish oilseed rape as a major crop. One of our objectives was to establish whether the drying and storage properties of double low varieties differed from those of traditional varieties. Also there are two species encompassed by the term rapeseed, *Brassica napus* and *Brassica campestris* and we tried to consider whether the differences between the two species are significant.

2. Seed properties

2.1 Physical

2.1.1 Size and shape

The only study found which investigated in detail the size, shape and mass of rapeseed was published by Scherer and Kutzbach (1978). Using winter rapeseed of variety Diamant harvested in 1976, they measured the diameter directly as 1.9 mm at 17.7% wet basis moisture, finding the seed virtually spherical and the mass as 5.69×10^{-3}g per seed. The equivalent sphere diameter (sphere with same volume as the seed) is, however, given as 1.8 mm, although this might be at a lower m.c. The relationships for average volume, V, m^3, as a function of moisture between 5.9 and 14.5% wet basis moisture is given as a function of moisture on a dry basis as

$$V = (0.0039 + 0.006M) \times 10^6 \qquad 2.1$$

The number of replicate measurements is unclear.

Jayas et al. (1987a) studied *Brassica Campestris* v Tobin and *B. napus* v Westar. The larger-seeded *B. napus* had an equivalent sphere diameter of 1.80 ± 0.008 mm while the smaller seeds of *B. campestris* were equivalent to 1.50 ± 0.025 mm. However, to obtain these values, the volume of 1000 kernels was measured with an air comparison pycnometer which would also have taken into account the surface pores in the seed so that the calculated apparent seed volume would have been less than that obtainable by direct measurements. The smaller values obtained by Jayas et al. compared to those of Scherer and Kutzbach supports this supposition.

Table 2.1

Properties of Tower variety of rapeseed as determined by Patil and Ward (1988)

Moisture content, % w.b.	Average diameter, mm	Bulk density, kg/m^3
19.6	1.48	644
17.6	1.42	659
15.5	1.40	664
11.9	1.37	669
8.8	1.35	682
6.5	1.34	688

Patil and Ward (1988) made direct measurements on 40 seeds of the variety Tower, taken from samples rewetted to moistures between 6.5 and 19.6% wet basis. The effect of increasing moisture was to cause an increase in average diameter from 1.34 to 1.48 mm. Results, given in Table 2.1, were related over this moisture range by the equation

$$D_{av} = (1.27 + 0.01W) \times 10^{-3} \qquad 2.2$$

A much better fit would have been obtained by omitting the point for 19.6% for which a particularly large increase in diameter was recorded. The values tabulated are considerably smaller than those of Jayas et al.

and Scherer and Kutzbach and though this might be a species difference, it is not stated whether Tower variety was *B. napus* or *B. campestris*.

The linear relationship with moisture of volume, Eqn. 2.1 and diameter, Eqn. 2.2 are not strictly compatible, as the volume of a sphere is proportional to the cube of the diameter but could be used over the limited range of diameter change. The linear relationship of Patil and Ward, Eqn. 2.2 for which r = 0.88 even with the 19.6% moisture value, is perhaps more convincing than that of Scherer and Kutzbach's Eqn. 2.1 for which r = 0.85 and no data was given. Using Eqn. 2.2, the fractional increase per % m.c. in the diameter at zero moisture would be 0.01/1.27 = 0.0079 per % m.c. A seed at 10% m.c. would therefore be expected to be 1.079 times its zero m.c. diameter.

2.1.2 Seed mass

The mass of seeds is normally expressed as the mass of 1000 seeds, to give a more meaningful number and to ensure a representative sample. Automatic counters make the task routine.

Scherer and Kutzbach (1978) measured the 1000 seed mass of Diamant variety of rapeseed as 5.69 g at 17.7% m.c., which gives a dry mass of 4.68 g. Then, by definition, the wet mass would be

$$S = 0.00468(1 + M) \qquad 2.3$$

No other systematic study was found. Many workers report the 1000 seed mass of their experimental samples but taken in isolation these measurements are not useful.

2.1.3 Solid density, bulk density and porosity

Definition: The solid density, ρ_s is the mass of seed matter divided by the net volume occupied by the seed itself, i.e. excluding air spaces (voids) between the seeds. The volume of air spaces within the seed pores may be included or excluded depending on the method of measurement, by gas or liquid immersion respectively, and the pressure applied. Bulk density, ρ_b, is the seed mass per unit of gross volume, i.e. including the void space. The ratio of volume of void to gross volume is termed the porosity, ϵ, and is calculated by $\epsilon = 1 - \rho_b/\rho_s$.

Units and symbols:

Solid density	kg/m^3	ρ_s
Bulk density	kg/m^3	ρ_b
Porosity	fraction	ϵ

Use: Solid density is of limited interest in crop storage, whereas bulk density determines what mass and hence value of crop can be held in a dryer or storage container of given volume, and what mass of moisture must be removed to dry the seed per unit volume of container. Porosity is a major determinant of resistance to airflow through the crop during cooling and drying (see 3.1.2).

Patil and Ward (1988) found that solid density initially decreased and then increased as moisture increased from 6.5 to 19.6% w.b. They expressed their data for solid density of Tower rapeseed as a function of moisture as

$$\rho_s = 1094 - 6.25\ W + 0.305\ W^2 \qquad 2.4$$

Scherer and Kutzbach (1978) give 1119 kg/m^3 as the solid density at 17.7% m.c.w.b., and give a relationship with moisture as

$$\rho_s = 1126 - 62.2M \qquad 2.5$$

but the correlation coefficient for Eqn. 2.5 is only 0.52 which indicates a poor fit to the data. Muir and Sinha (1988) measured the solid density of four varieties of rapeseed which had a range of 1093 to 1120 and replicate measurements lay within ± 1.4 kg/m^3 at 8.1% m.c.w.b. using five replicates.

Bulk density has been recorded by many workers but is difficult to interpret because the degree of packing, and therefore the bulk density and the porosity, depends on the method used to fill the measuring container. By vibrating the container, or by filling slowly, the bulk density can be significantly increased compared with a more rapid fill. A method for controlling rate of flow into the container, such as provided by the "Avery" device, or controlled height of fall above the rising material surface, is essential if the results are to be meaningful. The packing also depends on the particle surface properties such as roughness and moisture.

Jayas et al. (1989) recorded loose and dense fill data, giving details of how the filling was done, for three replicate samples of Tobin and Westar varieties of rapeseed. Bulk density reduced with m.c. from 700 kg/m^3 at 6.5% to 688 kg/m^3 at 14.5% in loose fill. Dense fill for the same moistures produced values falling from 775 to 759 kg/m^3 (see Table 2.2), an average of 12% greater. Inclusion of chaff reduced bulk density and increased porosity. Fines might be expected to increase bulk density because they could occupy the original void space, but their effect was to reduce it. This may be because the fines were not dust but small whole seeds and broken seeds, too large to occupy the voids. Jayas et al. gives a linear relationship for bulk density, ρ_b, and for porosity, ϵ, as a function of the percentage by weight of chaff and fines

$$\rho_b \text{ or } \epsilon = A_1 + A_2E_C + A_3E_F \qquad 2.6$$

Values for A_1, A_2 and A_3 for loose and dense fill are given in Table 2.3.

Table 2.2

Properties of rapeseed as determined by Jayas et al. (1989)

Variety	Moisture content, % w.b.	"Loose fill"		"Dense fill"	
		Bulk density kg/m^3	Porosity	Bulk density, kg/m^3	Porosity
Tobin	6.5	700	0.384	775	0.318
"	10.3	696	0.397	759	0.343
"	14.5	688	0.408	759	0.347
Westar	6.7	675	0.389	741	0.329

Table 2.3

Coefficients of Eqn.2.6 for bulk density and porosity of rapeseed as functions of percentage of chaff and fines, from Jayas et al. (1989)

Property		Coefficient		
		A_1	A_2	A_3
			Loose fill	
Bulk density	ρ_b	700	-3.18	-1.21
Porosity	ϵ	38.2	0.32	0.15
			Dense fill	
Bulk density	ρ_b	773	-2.87	-1.50
Porosity	ϵ	31.7	0.31	0.18

Muir and Sinha (1988) recorded bulk densities for four varieties of rapeseed at 8.1% m.c. using a standard method prescribed by the Canadian Grain Commission, and a slower fill to give compacted samples. Standard fill gave a range of 664 - 687 ± 1 kg/m^3, while compact densities from 729 to 746 kg/m^3 were obtained. Five replicates were measured. Varietal difference was said to be significant in all four cases but, as no within-variety replicates were done, the conclusion is not supportable. The differences were, in any case, less than 3.5%.

Rao and Pfost (1980) give a linear correlation for bulk density with moisture based on data obtained, they say, from Timbers (1975). However, Timbers did not include his bulk density data in his paper, only comments on the results. He used a limited range of moisture contents, 5 - 10% w.b. and remarks that no general trend with moisture was indicated.

Patil and Ward (1988) give a correlation for bulk density of Tower variety valid over the moisture range 6.5 to 19.6%, for a zero-height-of-fill method as

$$\rho_b = 710.2 - 2.95W \qquad 2.7$$

indicating a small reduction as moisture increased, (see Table 2.1).

Working with the Torch variety of *B. campestris*, Moysey et al. (1977) found that bulk density reached a maximum of 730 kg/m^3 at around 8% m.c. wet basis and 19.4°C, falling steeply at higher moistures and more gradually at lower ones. The effect of increasing temperature between -4 and 19°C was to increase bulk density, which is the opposite of what might be expected from simple thermal expansion of the seed.

Scherer and Kutzbach (1978) give the correlation

$$\rho_b = 695.2 - 141M + 118M^2 \quad 2.8$$

for bulk density of Diamant variety over the range 5.3 - 14.5% wet basis. A decline of bulk density with moisture is indicated throughout the range. This is unlike the results of Moysey' et al. (1977) but is supported by those of Jayas et al. (1987a) for *B. campestris* variety Tobin over the moisture range 6.5 - 14.5% w.b.

Porosity, calculated from the bulk and solid density or measured directly, is dependent upon the degree of packing of the particles and is therefore influenced by the method of fill, degree of vibration and surface properties.

Scherer and Kutzbach (1978) correlate their data with an expression which does not produce sensible results, perhaps because of a misprint, but the graphed data suggest that ϵ is virtually independent of moisture and that it lies in the range 0.39 - 0.40 over their moisture range of 5.3 to 14.5% w.b.

Patil and Ward's (1988) results for "Tower" variety show that between 6.5 and 19.6% w.b. moisture porosity increased from 0.345 to 0.40, and they give the correlation

$$\epsilon = 0.32 + 0.004W \quad 2.9$$

Jayas et al. (1989) give porosity values ranging from 0.318 to 0.408 for clean seed depending on fill method (Table 2.2). When 25% by mass of chaff was included the porosity rose from 0.384 to 0.476 in loose fill. The same percentage of fines raised it to 0.421. This perhaps suggests that uncleaned seed should be easier to ventilate and therefore preferable to clean seed but, unlike these experiments, fines and chaff in practice tend to be concentrated in heaps under discharge points. Because the spaces between fine particles are smaller, the resistance to airflow in these regions of the store is higher for seed and fines than for clean seed for the same porosity (Jayas and Muir, 1991). A further reason to clean the seed is that the moisture content of dockage from rapeseed has been found by Prasad et al. (1978) to be higher than that of clean seed by more than 4 percentage points of moisture, unlike wheat for which the dockage was 1% point drier. Jayas et al. (1989) gives a correlation for porosity for a loose fill mix of seed chaff and fines as

$$\epsilon = 0.382 + 0.0032E_C + 0.0015E_F \quad 2.10$$

and for dense fill

$$\epsilon = 0.317 + 0.0031E_C + 0.0018E_F \quad 2.11$$

where E_C and E_F are respectively the percentage by weight of chaff and of fines in the sample.
Muir and Sinha (1988) tested four varieties at 8.1% m.c. and found a range of only 0.33 - 0.34 after a free fall of 2.7 m. They concluded that the porosity of clean seed is independent of variety.

No investigations were found of the effect on porosity or bulk density of pressure exerted by deep beds of seed despite anecdotal evidence that the density of seed in deep bins increases during prolonged storage.

2.1.4 Friction and free surface characteristics

Definitions:

Filling angle of repose is the included angle between the horizontal and the sloped upper surface of a cone of grain created by the fall of grain at zero velocity onto a free surface of grain. The slope must be measured at some distance from the area of impact where the falling grain strikes and flattens the apex of the cone.

Emptying or draining angle of repose is the included angle between the horizontal and the sloped upper surface of a grain pile created when grain is allowed to flow out through an opening at the bottom or side of the pile.

Coefficient of sliding friction is the ratio of the force required to slide grain over a surface to the normal force pressing the grain against the surface.

Use:

These characteristics of the grain are needed to design conveying systems, and to calculate the capacity and structural strength of storage bins and dryers.

Data covering the moisture range 4.7 to 14.5% w.b. by Scherer and Kutzbach (1978) were correlated by a quadratic function of m.c. which has a minimum value of 21.5° at 20.9% w.b. However, this does not agree with their graphed data which show a minimum in a region with no data points at ≈ 11% w.b. of less than 21°. The actual values lie between 21 and 23° showing no trend with m.c., so the use of a quadratic function of moisture to describe them is very questionable.

Muir and Sinha (1988) found no differences in angle of repose between rapeseed cultivars, and only small differences between filling and emptying angles. At 8.1% w.b. filling angle was 24° while emptying angle was between 25 and 27°. Five replicate measurements were made. The effect of moisture was not investigated for rapeseed. No other data were found, so the effect of m.c. on angle of repose does not seem to be available.

Munroe and Moysey (1974) measured the coefficient of friction for rapeseed at moistures from 7.2 to 12.5% w.b. on seven material surfaces. The results showed little effect of m.c. on friction except for concrete surfaces. Values are given in Table 2.4. Values are much lower than for cereal grains, so lateral pressures in deep bins of rapeseed will be much higher than in similar bins of wheat, particularly if the bins are of concrete or timber.

No investigation has been found which examines cohesion or increased friction, as a result of settling over time or under the influence of pressure in deep beds, which can cause problems during emptying.

Table 2.4
Coefficients of friction of rapeseed on various surfaces
(from Munroe and Moysey (1974))

Surface Material	Moisture content of seed, % w.b.			
	7.2	8.7	10.0	12.5
Galvanised steel	0.25	0.20	0.23	0.23
Teflon	0.19	0.27	0.28	0.20
Plywood (perpendicular to grain)	0.36	0.34	0.35	0.36
Plywood (parallel to grain	0.35	0.33	0.35	0.37
Polyethylene on plywood	0.27	0.28	0.31	0.25
Contrete (wood float)	0.28	0.34	0.36	0.38
Concrete (steel trowel)	0.28	0.34	0.35	0.36

2.2 Moisture content

2.2.1 Methods of measurement

For most purposes, including trading, moisture content W is defined as the percentage of water by mass in the wet material, i.e. it is expressed on a 'wet basis'. By this definition

$$W = 100w/(w + m) \qquad 2.12$$

where m is the mass of dry matter. Note that the denominator, (w + m) in Equation (1) varies with W and is, therefore, not a constant base. Thus for engineering calculations, it is necessary to use the 'dry basis' moisture content, which is defined as the ratio of the mass of water to the mass of dry materials and has a constant denominator. i.e.

$$M = w/m \qquad 2.13$$

This ratio is analogous to that used to define the absolute humidity of air, i.e. the mass of water per unit mass of dry air. The dry basis moisture content is best expressed as a ratio, but for convenience is often expressed as a percentage. This practice can sometimes cause confusion with the wet basis value. 'Wet' and 'dry' basis values are related to each other by equations (2.14) and (2.15)

$$W = 100(M/(1 + M)) \qquad 2.14$$

$$M = W/(100 - W) \qquad 2.15$$

Whilst some moisture may be present in wet seeds in the form of free water, some of it, and in dry seeds most of it, will be in some form of chemical combination with other substances contained within the plant cells. Thus the absolute value of moisture content is not easy to define or determine. In practice it is defined by reference to a standard method of extraction and for rapeseed the reference method is BS4289:Part3(BSI, 1978). This standard, which is identical with the International Standard ISO 665-1977, specifies that 5 to 10 g samples of whole seed are dried to constant weight in a ventilated oven set to operate at 103°C ± 2°C. The results of two determinations should lie with 0.2% of each other.

The problem with the reference method is that it takes several hours to execute, and, in commerce, it is often more convenient, albeit less accurate, to use a far more rapid method. For merchants, mills and the larger stores, an infra-red reflectance analyser may be preferred because of its ability also to measure oil and protein content. Prescriptions for the calibration (against at least 40 oven moisture determinations) and use of the infrared reflectance analyser are given in BS4289:Part 6(BSI, 1986). Duplicate determinations of moisture content obtained with this class of instrument should not differ by more than 0.3% moisture content.

Two other indirect but rapid methods of assessing moisture content are used in a variety of electronic moisture meters. Conductance meters measure the conductivity of a ground sample of the seed compressed between two electrodes. The Marconi and Protimeter moisture meters are two examples of this type. The other type of meter is based upon measuring the change in capacitance or dielectric constant of a material with a change in moisture content. The Nickerson (or Burrows) and Sinar Agritek are examples of meters of this type.

It is convenient to distinguish three aspects of accuracy:-

(1) the repeatability of readings on the same sample. This can be quantified by calculating the coefficient of variation of a number of separate readings on the same sample.

(2) the accuracy of the calibration over the working range of the meter. For an ideal meter the indicated moisture content would correspond exactly with the oven moisture content over the whole range. In practice, a plot of the moisture contents given by the meter calibration and the oven determination will show deviations from a straight line at 45° passing through the origin. Thus a meter may give readings which are consistent but are more or less in error, depending upon the position of the reading on the calibration curve.

(3) the error caused by differences in dielectric properties between the seed samples used for calibration and those for which the meter is used in commerce.

This third source of error, taken together with the difficulty of obtaining representative samples of large bulks is a common source of dispute over moisture contents. No solution is offered in this review.

The Marconi moisture meter is now no longer manufactured but many remain in regular use both on-farm and at merchants. An independent test (NIAE, 1970) on the models TF933A and TF933B showed that the calibration chart, Chart 168, was to be preferred to the composite calibration chart, A3, for moisture contents in the range 4 - 10% and a new set of values was suggested to cover the band from 10 - 21%. The accuracy of the meters was summarized by a table, Table 2.5, showing the percentage of measurements which came within five arbitrarily selected error bands. In the moisture range 4 - 10%, just over half the readings were within ± ½% m.c. and none were greater than ± 2% m.c. in error. But for many purposes an error of more than 1% m.c. cannot be regarded as acceptable.

Table 2.5

Percentage of measurements with the Types A and B of the Marconi TF933 moisture meter which fell within arbitrarily selected error bands about the overall calibration curves (NIAE, 1970)

Error band %w.b.	Percentage of points within error band			
	4 - 10% m.c.		10 - 21% m.c.	
	Type B	Type A	Type B	Type A
± ½	52	53	30	26
± 1	83	70	44	39
± 1½	100	93	74	68
± 2		100	81	77
± 3			100	100

At high moisture contents (10 - 21%) the accuracy of the meter was worse and an error band of ± 3% m.c. was needed to contain all the data.

Further information on the conductance type of meter comes from tests conducted by the Prairie Agricultural Machinery Institute in Canada (PAMI, 1977 a - j). Four conductance meters were tested but only 2, the Skuttle MT2 (PAMI, 1977 c) and the Protimeter TW73 (PAMI, 1977 h), a British meter, had been calibrated for rapeseed. The test results (Table 2.6) are a useful illustration of the problems of using electronic moisture meters.The repeatability was expressed by the coefficient of variation given by five separate readings of the sample. The larger of the two coefficients of variation given for the conductance meters was that for the Skuttle MT2, at 1.08%. This implies that on a sample of 10% m.c., the standard deviation would be ± 1.08% m.c. and that the standard error of the mean of 5 readings would be ± 0.48% m.c. Thus at the 95% level of confidence, the mean value could be between 8.7 and 11.3% m.c. (± 1.34% m.c.). The confidence in any one reading is therefore low. In contrast the coefficient of variation on the Protimeter, 0.05%, is very much smaller and implies an exceptionally high level of confidence in each reading.

TABLE 2.6
Results from moisture meter tests on Canadian rapeseed (PAMI, 1977 a-j)

	Regression equation	Simple Corr. Coeff.	S.E. of Estimate	Resid. Mean Square	Sample Size	Sample mean	Coeff. of Var, %	Range of tests		Ground ?	Weighed sample
								Min	Max		
Resistance meters											
Skuttle MT2	Y=0.37X + 7.49	0.84	0.57	0.32	5	12.46	1.08	6.5	16	No	No
Protimeter TW73	Y=0.32X + 4.95	0.89	0.51	0.36	10	8.50	0.05	6.5	16	Yes	No
Delmhorst G-6B	R=6.85X - 28.76	0.86	11.79	138.99	10	47.52		6.5	16	No	No
RDS Grain-O-Meter	R=0.52X - 9.3	0.95	0.61	0.38	8	15.19		6.5	16	No	No
Capacitance meters											
Agtek-35	Y=1.09X - 0.76	0.97	0.90	0.65	10	11.35	0.65	6.5	16	No	No
CAE 101-A	Y=1.04X - 0.70	0.99	0.43	0.18	10	10.85	0.17	6.5	16	No	60/80g
Dole 400 (PB-70-11)	Y=1.03X - 1.15	0.99	0.48	0.21	10	12.58	0.23	6.5	16	No	142g
Labtronics 919	Y=1.01X - 0.06	0.99	0.54	0.29	24	16.01	0.35	7.1	16	No	125/175g
Qwik-Test	R=3.68X - 22.16	0.98	1.60	2.57	6	12.07		6.5	13	No	227g
Dickey-John Farm	R=2.29X - 7.25	0.99	1.05	1.10	10	17.07		6.5	16	No	200g

Y = meter reading in moisture content, per cent wet basis

X = oven moisture content, per cent wet basis

R = meter reading, uncalibrated units

The calibrations of the conductance meters are not good. For the Skuttle MT3 a correlation coefficient of 0.84 reflect errors in the calibration from + 0.56% to - 2.27% m.c. over a range of oven readings from 11 to 15.5% (Fig.2.1). The correlation coefficient for the Protimeter, 0.89 is slightly better but reflects a change from +0.53 to - 5.59% m.c. over the whole range, 6.5 to 15.5%, of moisture contents used. One reason for these discrepancies is, of course, that the original calibration was carried out with rapeseed having different electro-chemical properties to that used in the tests. It is possible that the meters could be recalibrated, but it is doubtful whether such recalibration would have universal validity. The present evidence does not inspire much confidence in the conductance type of meter available in 1977. Also, Stenning and Channa (1987) report work with the Marconi TF933C which emphasised the need for the calibration of each variety for this conductance meter.

Six capacitance type meters (PAMI, 1977, a,b,d,e,i,j) were tested at the Prairie Agricultural Machinery Institute and the results are also summarised in Table 2.2 Here again, not all of the meters had been calibrated for rapeseed. With the exception of the Agtek-35 (known in the UK as the Wile 35), the capacitance meters used a weighed sample of unground grain to provide compensation for variation in bulk density. Not surprisingly the Agtek-35 had the highest coefficient of variation (lowest repeatability) of the four for which a manufacturer's calibration was available. Nevertheless the repeatability is well within acceptable limits. In all four cases the correlation between the meter and oven moisture contents is high and reflects slopes close to unity in the regression equation (Table 2.6, Fig.2.1). The largest differences from the oven reading over the whole range, 6.5 to 15.5%, are given by the Agtek-35 but they are small in the important range from 8 to 11%. The calibration of the Labtronics 919 was exceptionally good with deviation from the oven reading not exceeding 0.1% m.c. at worst.

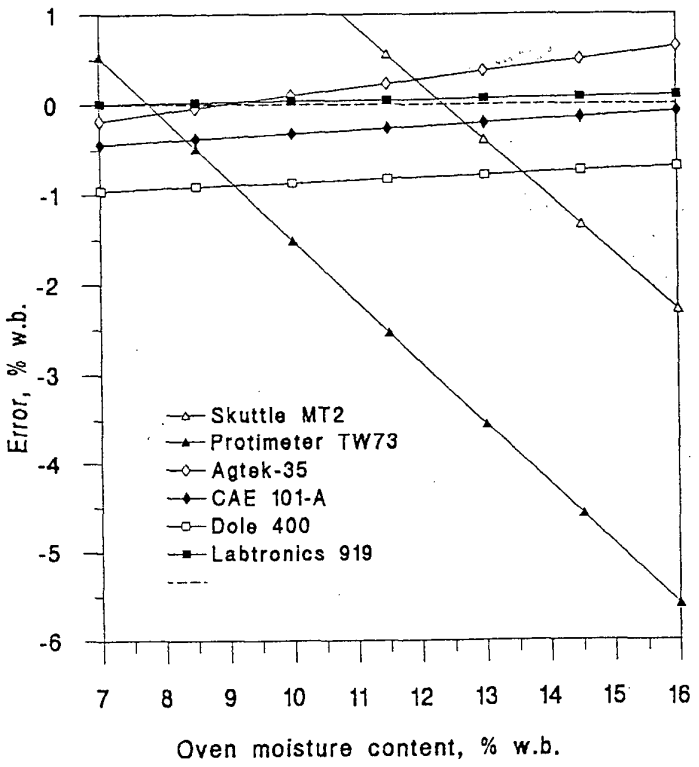

Fig.2.1. Linear component of difference between moisture content indicated by meter and moisture content determined by the oven method for 2 conductance (Skuttle & Protimeter) and 4 capacitance meters

The message from these Canadian results appears to be that the calibration of the capacitance type of meter may be less sensitive than the conductance type to changes in variety and type, and that the capacitance type is capable of giving reasonably accurate results. No comparable work under UK conditions or with current varieties of rapeseed has been published.

2.2.2. **Equilibrium moisture content**

The equilibrium moisture content (emc) of the seed is that moisture content at which there is no moisture exchange between the seed and the surrounding air and at which, therefore, it is in moisture equilibrium with that air. Similarly the equilibrium relative humidity (erh) of the air is the humidity in equilibrium with the seed moisture content.

The emc-erh relationship is of importance for both physical and biological reasons. Physically it determines the response that seed makes to its surrounding atmosphere, i.e. whether it dries or wets, and in an enclosed space will determine the humidity within the air. This has biological relevance in that insect, fungal and bacterial activities are strongly influenced by air humidity. In particular at relative humidities in excess of 65%, moisture becomes only weakly held within the plant tissues and is easily made available for chemical reaction or utilization by microflora. Thus the equilibrium moisture content equivalent to an equilibrium relative humidity of 65% is often used as the level to which seed must be reduced for safe storage (Shatadal and Jayas, 1990).

For reasons more fully discussed by Shatadal and Jayas (1990) the plot of emc as ordinate against erh as abscissa is a sigmoid curve becoming asymptotic to 100% rh. Three main factors affect the position of these curves:-

1. Temperature. For a constant relative humidity, increasing the temperature reduces the equilibrium moisture content. Conversely for a constant moisture content, the equilibrium relative humidity will increase with temperature. This can have important implications for safe storage of seed moved from cold to warm climates.

2. Direction of moisture exchange. Sorption isotherms tend to exhibit 'hysteresis' and, for a given relative humidity, the desorption emc will be greater than the 'adsorption' value.

3. Method of measurement. The equilibrium condition can be found either by measuring the moisture content at which the seed comes into equilibrium with a controlled atmosphere (emc method), or by measuring the relative humidity generated by seed of known moisture content within a quantity of air little more than that contained within the interstitial spaces (erh method). The difficulty with the emc method is the time taken for the equilibrium to be reached and, for high humidities at near-ambient temperatures, the difficulty of preventing microbial deterioration. The method is more useful for low humidities, particularly those given by heating air as, for example, in the studies by Patil and Ward (1989) and Sutherland and Ghaly (1982) of the heated-air drying of rapeseed. However, most of the data to be quoted in this review were obtained by the erh method which not only has the advantage of speed but can be used at high moisture contents/relative humidities.

To compare and to unify data from different authors or to establish an effect such as hysteresis and to provide a ready means of using the data, it is necessary to express it in equation form. Shatadal and Jayas (1990) have reviewed some of the equations used for describing the emc/erh curve and explain that no one equation describes the curve well over the whole range of relative humidities. Sources of emc/erh data for rapeseed are summarised by Table 2.7.

Table 2.7
Sources of emc/erh data for rapeseed

Author(s)	Date	Variety	Method	Moisture	Temp, °C	Comments
Pichler, H.J.	1956		Vap.P	0.-100% rh	20-80	Graphical only
Sijbring,P.H.	1963		Erh			Smoothed data
Kreyger, J.	1972		Erh			Smoothed data
Timbers, G.E. Hocking, R.P.	1974					
Pixton, S.W.		Gulle				Adsorption & Desorption
Warburton, S.	1977	Hektor Tower	Erh	20-90%rh	5-35	Smoothed data
Rao, V.G.			Emc &			
Pfost, H.B.	1980		Erh	30-90%rh	5-40	Adsorption, data not given
Pixton, S.W.				21.5-		Adsorption & Desorption
Henderson,S.	1981	Candle	Erh	92.3%rh	5-35	Smoothed data
Sutherland,J.W.				1.5-4.0%		
Ghaly, T.F.	1982	Tower	Emc	mcwb	40-70	Desorption. Numerical
Henderson,S.		Jet Neuf		22.7-92.6		Adsorption & Desorption
Wilkin, R.	1985	Bienvenu	Erh	39.9-89.0	5-25	Original data
		Fiona		30.5-82.2 % rh		
Sokhansanj, S Zhijie, W						
Jayas, D.						Adsorption
Kameoka, T.	1986	Tobin	Erh	18-90%rh	5-25	Original data
Patil, B.G.				2.2-4.6		Desorption
Ward, G.T.	1989	Tower	Emc	%mcwb	30-60	Original data
Shatadal, P. Jayas, D.S.				10.1-15.0		
White, N.D.G.	1989	Tobin	Emc	%mcwb	7.5-30	Desorption

Table 2.8
Coefficients in 5 equilibrium equations

Equation					Source	Data
Mod-Henderson	a_1	a_2	a_3			
Rapeseed meal	0.000103	89.99	1.613		Jayas et al, 1988	
Rapeseed-erh	0.001484	49.99	1.008		Rao & Pfost, 1980	
Rapeseed-emc	0.000143	146.56	1.723		Rao & Pfost, 1980	
Candle	0.000577	46.79	1.431		Muir & Sinha, 1986	Pixton & Henderson, 1981
Tobin	0.000506	40.12	1.570		Sokhansanj et al, 1986	
Chung-Pfost	b_1	b_2	b_3			
Rapeseed meal	519.2	13.90	107.60		Jayas et al, 1988	
Rapeseed-erh	91.4	12.76	37.13		Rao & Pfost, 1980	
Rapeseed-emc	694.2	28.23	116.14		Rao & Pfost, 1980	
Tobin	189.1	21.12	39.18		Sokhansanj et al, 1986	
Mod-Halsey	c_1	c_2	c_3			
Tower	2.875	0.00748	1.701		Chen & Morey, 1989	Pixton & Warburton, 1977
Candle	3.003	0.00490	1.761		Chen & Morey, 1989	Pixton & Henderson, 1981
Tobin	3.489	0.01055	1.860		Chen & Morey, 1989	Sokhansanj et al, 1986
Mod-Oswin	d_1	d_2	d_3			
Tobin	8.123	-0.04539	2.397		Chen & Morey, 1989	Sokhansanj et al, 1986
Strohman-Yoerger	s_1	s_2	s_3	s_4		
Canola	0.277	-0.10870	-2.105	-0.118	Sharma & Muir, 1974	Interpolated data of Pichler, 1956
Guggenheim-Anderson-de Boer	M_o	p_1	p_2			
Adsorption	.0355	10.63	0.876		Lomauro et al, 1985	Pixton & Warburton, 1977
Desorption	.0350	19.30	0.881			
Rapeseed*	2.86	16.34	.009		Burghart, 1984	Unknown

* Moisture content expressed in % wet basis

Table 2.9

Popular isotherm equations examined by Chen and Morey (1989)

Modified-Henderson (Eqn.2.17) $M_e = \left[- \frac{\ln(1 - \varphi)}{a_1 (T + a_2)} \right]^{\frac{1}{a_3}}$	$\varphi = 1 - \exp(-a_1 (T + a_2) M_e^{a_3})$
Chung-Pfost (Eqn.2.18) $M_e = -\frac{1}{b_3} \ln \left[\frac{- \ln\varphi \ (T + b_2)}{b_1} \right]$	$\varphi = \exp \left(- \frac{b_1}{T + b_2} . \exp (-b_3 M_e) \right)$
Modified-Halsey (Eqn.2.19) $M_e = \left[- \frac{\ln\varphi}{\exp(c_1 - c_2 T)} \right]^{-\frac{1}{c_3}}$	$\varphi = \exp (-\exp (c_1 - c_2 T) M_e^{-c_3}$
Modified-Oswin (Eqn.2.20) $M_e = (d_1 + d_2 T) . \left[\frac{\varphi}{1 - \varphi} \right]^{\frac{1}{d_3}}$	$\varphi = \frac{1}{\left(\frac{d_1 + d_2 T}{M_3} \right)^{d_3} + 1}$ or $1/\varphi = \left[\frac{d_1 + d_2 T}{M_e} \right]^{d_3} + 1$

The early work of Pichler (1956) remains unique in covering such a wide range of temperatures (20 - 80°C) up to relative humidities over 90%, but unfortunately the data were presented graphically only. An attempt was made to use the original equation of Henderson (1952) but a satisfactory description of the results was not found. Sijbring (1963) published numerical but smoothed desorption data measured for the single temperature, 25°C and this was later expanded by Kreyger (1972) in his compilation of many years work at Wageningen. Later Sharma and Muir (1974) fitted Pichler's data to the equation of Strohman and Yoerger (1967):

$$\varphi = \exp(s_1 \exp(s_2 M_e) \cdot \ln(P_s) + s_3 \exp(s_4 M_e)) \qquad 2.16$$

Where the coefficients s_1, s_2, s_3 and s_4 were found to be 0.2772, -0.1087, -2.1050 and -0.1180 respectively. This equation is not easily solved for M_e and in later work on the simulation of the drying and storage of rapeseed, Muir switched first (Muir and Sinha, 1986) to using the data of Pixton and Henderson (1981) for the North American variety Candle, fitted to the Modified Henderson equation (see Table 5) and then (Muir et al. 1989) to the data of Sokhansanj et al. (1986) also fitted to the Modified-Henderson equation. Some authors quote the work of Timbers and Hocking (1974) but the report has not been available to the authors of this review.

The first authors to report data for named varieties of rapeseed (Gulle, Hektor and Tower) for both absorption and desorption and over a range of temperatures (from 5 to 35°C) were Pixton and Warburton (1977). Their data were presented as tables of moisture contents (on a wet basis) for uniform increments of relative humidity and no attempt was made to fit an isotherm equation. Subsequently, however, these data have been used by several other investigators to explore the applicability to rapeseed of the more commonly accepted isotherm equations. Using the same apparatus and method of determination, Pixton and Henderson (1981) determined equilibria for the variety Candle and this time presented the data as equilibrium relative humidities for uniform increments of moisture content. Further data for the adsorption equilibrium of the varieties Jet Neuf, Bienvenu and Fiona and desorption of Jet Neuf and at temperatures from 5 to 25°C were added by Henderson and Wilkin (1985). These data were not smoothed but, although they were not fitted to a recognised isotherm equation, a log-log transformation was used to linearise the data and compare the logarithmic means and confidence limits for all the varieties investigated by Pixton, Henderson and their collaborators. Rao and Pfost (1980) measured the equilibrium of an unnamed variety of rapeseed by both the 'emc' and the 'erh' method and fitted their data to the Modified Henderson and the Chung-Pfost equation (see Table 2.8). The original data values were not tabulated. The use of electronic capacitance moisture sensors to measure seed and air moisture content reduced the accuracy of this work compared with the work originated by Pixton at Slough where seed moisture contents were determined by the oven method and relative humidity by cooled-mirror sensing of the dewpoint. Sokhansanj et al. (1986) measured adsorption data for the Canadian variety, Tobin, using a method similar to that of Pixton. Dewpoint was sensed by a lithium-chloride cell which was claimed to be accurate to ± 4% relative humidity at 75% relative humidity. This is noted here to emphasise that data are determined to varying degrees of accuracy and the possibility of considerable error in measuring both moisture content and relative humidity means that comparisons between data sets can be difficult and liable to lead to false conclusions.

The data of Sokhansanj et al. (1986) agreed well with the data of Pichler (1957), Timbers & Hocking (1974) and Pixton & Henderson (1981) but not well with values predicted by Rao & Pfost (1980). The modified Henderson equation fitted the data slightly better than the Chung-Pfost but both equations under-predicted the emc at relative humidities above 80%.

Lamauro et al. (1985) fitted the data of Pixton and Warburton (1977) as reported in Gough & Lippiatt (1977) to four isotherm equations. Acceptable fits were given by the Halsey, Oswin and the Guggenheim-Anderson-de Boer (GAB) equations but the fits to the Halsey and Oswin equations have now been superseded by the work of Chen & Morey (1989). The GAB equation is:

$$\frac{M_e}{M_o} = \frac{p_1\, p_2\varphi}{(1 - p_2\varphi)(1 - p_2\varphi + p_1\, p_2\varphi)} \qquad 2.21$$

where M_o = moisture content equivalent to a monolayer of absorbed water. Values of M_o and of the coefficients p_1 and p_2 for adsorption and desorption are given in Table 2.8.

Burghart (1984) reports values for the coefficients in an equation which is essentially the GAB equation except that moisture contents were expressed on a wet basis and so the coefficients cannot be compared with those obtained by Lamauro et al. (1985). Also Burghart does not state the origin of his data.

Chen & Morey (1989) fitted data for the varieties Candle (Pixton & Warburton, 1977), Tower (Pixton & Henderson, 1981) and Tobin (Sokhansanj et al., 1985) to four equations (Table 2.9) and assessed their suitability mainly by inspection of the residuals (difference between predicted and observed relative humidity) plotted against the predicted relative humidity. Systematic deviations were found with the Modified-Henderson and Chung-Pfost equations and only in the case of the Tobin variety was the Modified-Oswin equation acceptable. The Modified-Halsey equation provided the best fit to all three varieties. The parameters are given in Table 2.8.

For the purpose of this review, all the available data of reasonable provenance have been assembled and are presented numerically in the Appendix. They comprise 326 observations from 22 different data sets encompassing 184 and 142 results for adsorption and desorption respectively. In various groupings of desorption and adsorption and/or variety, these data were fitted, using the statistical package GENSTAT (Payne et al., 1988) to the Modified-Henderson, Modified-Halsey and Nellist and Dumont (1979) equations. The Nellist/Dumont equation was fitted because of its use in our own (Nellist, 1987, Bruce, 1984) and other (e.g. Smith, 1982) drying simulation programs. Inspection of the residuals and of the residual error variance confirmed Chen & Morey's (1989) conclusion that the Modified-Halsey equation gave the best fit and only the coefficients for that equation are presented here (Table 2.10).

Fig.2.2 shows the isotherms for 5° and 35°C predicted by the fit to all the data superimposed upon a scatter plot of all the data. Fig.2.3 again shows isotherms for 5° and 35°C but this time differentiated between adsorption and desorption. The apparent hysteresis is greater at 35°C than 5°C and tends to disappear or even to reverse at high humidities. Clearly this separate fitting of the desorption and adsorption data does not resolve satisfactorily the effect or existence of hysteresis. Accordingly for a more thorough examination of this effect we restricted our attention to those data sets (Pixton and Warburton, 1977; Pixton and Henderson, 1981; Henderson and Wilkin, 1985) for which nearly equal quantities of adsorption and desorption data were available. Given the non-linear nature of the curves and the equations used to describe them it was not possible to carry out a conventional parallel-curve analysis. The solution was to use the factor level facility within GENSTAT to force the difference due to hysteresis on to only one of the coefficients. In the case of the Modified-Halsey equation, for example, c_1 has two values, one for adsorption and one for desorption, but c_2 and c_3 remain the same. The set of coefficients is given in Table 2.11. Note firstly that the fits are very good

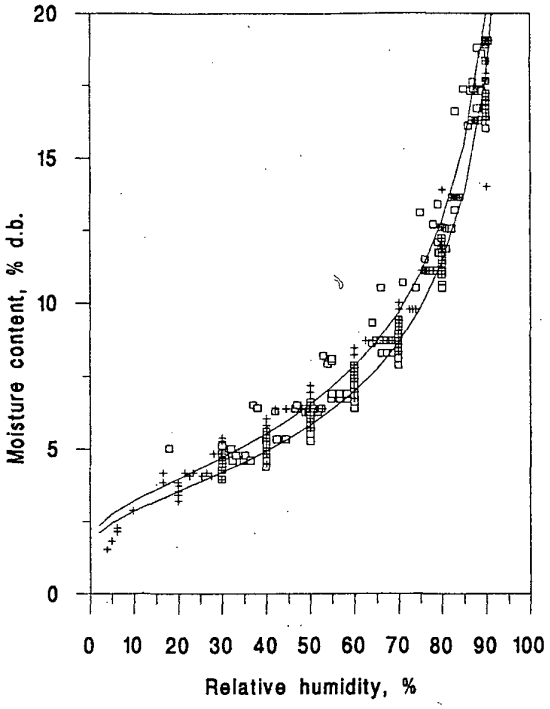

Fig.2.2 Isotherms at 5°C (upper) and 35°C (lower) given by the Modified-Halsey equation fitted to the data for adsorption (□) and desorption (+) collected in Appendix 1.

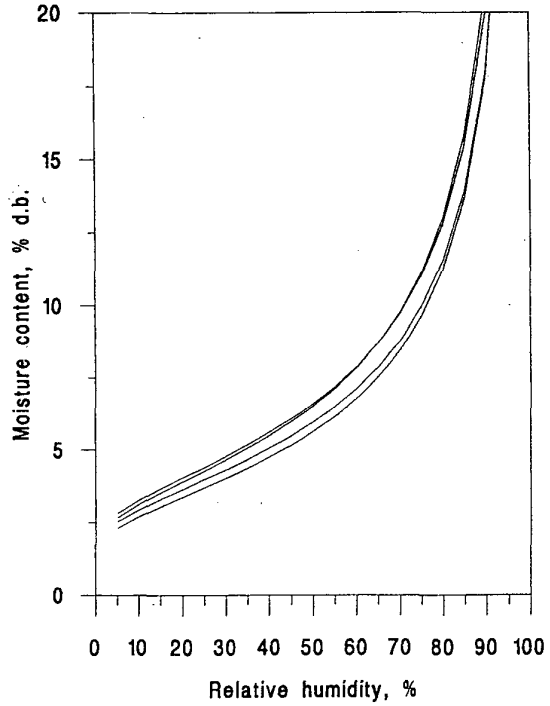

Fig.2.3 Isotherms at 5°C (upper pair) and 35°C (lower pair) given by the Modified-Halsey equation fitted separately to all the adsorption and desorption data gathered in Appendix 1 and showing that the effect of hysteresis is more marked at the higher temperature.

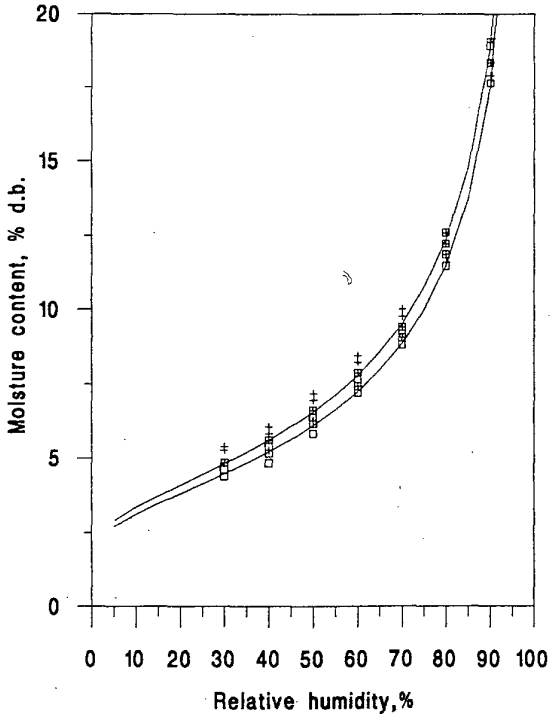

Fig.2.4 Desorption (top) and adsorption (bottom) isotherms at 25°C given by the fit of the Modified-Halsey equation to the data for Tower rapeseed, with the hysteresis effect expressed through the value of coefficient c_1 only.

(>99.4% variance accounted for in every case) and secondly that the drift in the value of c_1 is the consistent for each data set. This suggests that the hysteresis effect is real, albeit small, and ensures also that the hysteresis is predicted as a shift in the sigmoid curve which is conceptually correct. Fig.2.4 illustrates this shift for the 25°C isotherms.

3. Heating and drying characteristics

3.1 Physical

3.1.1. Specific heat capacity

Definition: The specific heat capacity of a substance is the quantity of heat required to raise unit mass of the substance through unit temperature rise at constant pressure

Units: J/(kg K) Symbol: c_p

Use: The specific heat is needed to calculate changes in the temperature of the crop when heat is added, perhaps by ventilating with heated air or by respiration activity of the crop itself, or when heat is removed during drying, cooling or chilling.

Table 2.10

Coefficients in the Modified-Halsey equation for
8 varieties of rapeseed in adsorption and desorption

	Adsorption			Desorption			Adsorption and Desorption		
	c_1	c_2	c_3	c_1	c_2	c_3	c_1	c_2	c_3
Gulle	2.747	.00643	1.707	2.782	.00750	1.679	2.778	.00698	1.697
Hektor	2.586	.00532	1.664	2.764	.00794	1.655	2.705	.00717	1.667
Tower	2.885	.00659	1.707	3.348	.00808	1.866	3.050	.00724	1.755
Candle	3.022	.00490	1.769	3.161	.00747	1.791	3.116	.00622	1.790
Jet Neuf	2.594	.00536	1.592	2.813	.00502	1.705	2.716	.00519	1.655
All	2.671	.00614	1.641	2.848	.00708	1.680			
Bienvenue	2.712	0.00561	1.674						
Fiona	3.002	0.00550	1.798						
Tobin	3.415	0.01191	1.820						
All	2.756	0.00812	1.644	2.879	.00571	1.705	2.828	.00653	1.684

Table 2.11
Results of fitting the Modified-Halsey equation to 5 data sets for which desorption and adsorption data were available and for which the effect of hysteresis has been restricted to the value of c_1 only

Variety	Gulle	Hektor	Tower	Candle	Jet Neuf
Nos. of data - adsorption	27	24	27	28	15
desorption	32	28	27	31	15
	59	52	54	59	30
% variance accounted for	99.7	99.4	99.7	99.8	99.7
Coefficients					
c_1 adsorption	2.735	2.609	3.039	3.073	2.708
c_1 desorption	2.790	2.752	3.170	3.115	2.722
c_2	0.00705	0.00676	0.00732	0.006294	0.00518
c_3	1.689	1.661	1.782	1.780	1.654

The specific heat of rapeseed has both been measured directly and calculated from other measurements. As with other seeds the specific heat increases with both moisture content and temperature. The correlations developed by authors assume that the moisture and the dry matter may be regarded as independent.

Rao and Pfost (1980) used a calorimetric method based on toluene which is immiscible with water and is not absorbed by the seeds. This method allows the seeds to be mixed with the fluid and gives rapid equilibration and a larger temperature change to be measured than the more conventional method of enclosing the seeds in a container which is immersed in water. It is not clear if the possibility of reaction of toluene with the oil content of the seeds was considered. Rao and Pfost gave a general equation for any material with separate coefficients for its components such as protein, ash, fat, etc., but as no coefficient was given for fibre the equation does not seem to be usable. For rapeseed they gave as a correlation, with wet basis moisture content

$$c_p = 1245 + 33W \qquad 3.1$$

but no data were given. The moisture range for which the correlation was valid is not stated but from other information given by the authors the moisture range can be deduced as approximately 4 - 15% wet basis. The temperature range and number of replicates for each condition were not given.

Sharma and Muir (1974) presented a correlation which they determined using the data of Small (1972) for a temperature range from 10.2 - 20.6°C which is ideal for near-ambient drying studies, though the moisture range was not given. The correlation was presented in terms of dry basis moisture as

$$c_p = 1394 + 20.5M \tag{3.2}$$

which converted to wet basis becomes

$$c_p = 1394 + 2050W/(100-W) \tag{3.3}$$

Burghart (1989) gave a correlation reputedly from Mattei dating from 1969 but the reference could not be traced.

$$c_p = 1269 + 29W + 5.9T \tag{3.4}$$

Moysey et al. (1977) calculated the specific heat from their other measurements using the relationship.

$$c_p = \lambda/(\alpha \rho_s) \tag{3.5}$$

Data values were given (Table 3.1) tabulated against moisture (0.8 - 19.6% w.b.) and at the temperatures, -4.4, 1.7 and 19.4°C. Regressions were presented by Moysey et al
for 19.4°C as

$$c_p = 1356 + 32.0W \tag{3.6}$$

for 1.7°C as

$$c_p = 1288 + 28.4W \tag{3.7}$$

and for -4.4°C as

$$c_p = 1328 + 28.0W \tag{3.8}$$

Muir and Sinha (1986) used the data of Moysey et al. (1977) to develop three correlations including a temperature term for three ranges of moisture and temperature. For temperatures below 0°C very poor correlation was obtained. Giving T > 0°C and W > 1% as the range, they presented

$$c_p = 1265 + 30W + 5.95T \tag{3.9}$$

For T > 0°C and W < 10% they gave

$$c_p = 1290 + 33W + 0.24T \tag{3.10}$$

but the given moisture ranges of these correlations overlap.

Looking at the data one can see the temperature ranges of the correlations to be 1.7 -19.4°C in both cases, and the moisture range to be 0.75 to 5.5% w.b. for the first, 5.5 to 19.6% w.b. for the second.

Timbers (1975) equilibrated five cultivars of rapeseed, whole and ground, with air at 11 and 67% relative humidity, giving moisture contents of approximately 3.8 and 9.7% w.b. The temperature used was not specified. No significant differences in the specific heat capacity between cultivars were observed. Data on whole rapeseed, Echo cultivar, at moistures between 3.8 and 9.7% w.b., given in Table 3.2 were correlated by

$$c_p = 1290 + 67W \qquad 3.11$$

The moisture coefficient, 67, was considerably higher than presented by other workers, whose values as given above lie in the range 20 - 33. Thus use of Eqn. 3.11 beyond its stated moisture range would give rise to significant differences from the predictions of several other workers.

No data on specific heat capacity of rapeseed is given in ASAE D243.2 (1982) suggesting that the committee did not consider the available data was sufficiently sound for inclusion. For comparison the specific heat of wheat, given in ASAE D243.2 and converted to SI units, can be expressed as

$$c_p = 1398 + 41W \qquad 3.12$$

The specific heat of rapeseed is slightly lower than that of wheat mainly because of the lower specific heat of the oil components of rapeseed.

3.1.2 Thermal conductivity

Definition:	The thermal conductivity of a substance is the quantity of heat flowing across a surface of the material per unit time, area and temperature gradient.
Units:	W/(m K) Symbol: λ
Use:	The thermal conductivity is needed to calculate the rate of flow of heat at steady conditions for a given temperature gradient within the crop bed.

The thermal conductivity here refers to the properties of the bulk material including the air between the seeds, but because in any calculation of drying convective and conductive heat transfer would be calculated separately, the techniques used to determine thermal conductivity attempt to minimise any corrective transfer of heat due to movement of the interstitial air. Bilanski and Fisher (1976) gave averaged data for four replicates (Table 3.3) for temperatures from 4.4 - 31.7°C and moistures from 6.1 - 12.8% wet basis. Linear dependencies of thermal conductivity on m.c. and temperature are noted and correlation coefficients were given but the correlation equations were not. Values for whole seed range from 0.108 to 0.155 W/(m K). Ground seed had lower thermal conductivity, presumably because of the additional air present between the particles, though the bulk densities were not given. The thermal conductivity would be expected to depend on the size of the ground particles.

Moysey et al. (1977) tabulated their data as the mean of five thermal conductivity measurements with moisture from 0.75 to 19.6% w.b. and temperatures from -25.6 to 19.4°C. Values at -4.4°C and above (Table 3.1) increased with temperature and moisture from 0.0898 to 0.120 W/(m K) but no correlation equation was given. The effect of seed size was reported to be significant, the larger seed having higher thermal conductivity.

Table 3.1

Properties of Torch cultivar of rapeseed (from Moysey et al. 1977)For specific heat capacity and thermal conductivity each value is the mean of five tests. For thermal diffusivity, 15 tests were used to derive each value.

Temperature, °C	Moisture content, % w.b.				
	0.75	5.5	10.5	15.5	19.6
	# Specific heat capacity, J/(kgK)				
19.4	1385	1481	1778	1812	-
1.7	1305	1397	1661	1745	1807
-4.4	1372	1473	1590	1753	1904
	Thermal conductivity, W/(m K)				
19.4	0.0969	0.103	0.116	0.120	*
1.7	0.0929	0.104	0.113	0.115	0.113
-4,4	0.0898	0.100	0.105	0.109	0.108
	Thermal diffusivity, m2/s = tabulated value x 10^{-8}				
19.4	9.96	9.47	9.06	9.60	*
1.7	10.1	10.1	9.39	9.55	9.42
-4.4	9.52	9.60	9.39	9.21	9.19

Calculated from measured values of thermal conductivity and thermal diffusivity

* Sample moulded during test

Table 3.2

Properties of Echo Cultivar of rapeseed (from Timbers, 1975)

Moisture content, % w.b.	Specific heat capacity, J/(kg K)	Thermal conductivity, W/(m K)	Thermal diffusivity, m2/s = tabulated value x 10^{-8}
3.8	1540	0.105	9.7
4.4	1545	0.105	9.5
5.0	1635	0.110	9.7
5.7	1730	0.118	1.0
6.6	1740	0.126	1.0
8.1	1830	0.140	1.1
9.7	1930	0.147	1.1

Table 3.3

Thermal conductivity of rapeseed (from Bilanski and Fisher (1976)). Each value is the mean of four tests

Thermal conductivity, W/(m K)				
Moisture content, % w.b.	Temperature			
	4.4°C	12.8°C	23.3°C	31.7°C
6.1	0.108	0.109	0.115	0.118
8.0	0.117	0.119	0.123	0.127
11.5	0.125	0.131	0.136	0.146
12.8	0.137	0.141	0.147	0.155

Timbers (1975) calculated values for thermal conductivity from his other measured data using Eqn. 5 over the range 3.8 - 9.7% w.b. moisture. Values ranged from 0.105 to 0.147 W/(m K) (Table 3.2). No varietal difference was noted. As the values were calculated from thermal diffusivity and the thermal diffusivity values were higher than those reported by Moysey et al. (1977), the thermal conductivity values were also therefore higher than those of Moysey. No values for rapeseed are given by ASAE but ASAE D243.2 gives a correlation for wheat of

$$\lambda = 0.117 + 0.00113W \qquad 3.13$$

For the moisture range of Timbers' data, the calculated values for wheat lie in the range 0.121 to 0.128 W/(m K), showing similar values to those of Timbers for rapeseed but less of an increase with moisture.

3.1.3. Thermal diffusivity

Definition: The thermal diffusivity of a substance, defined as $\lambda/(\rho_s c_p)$, is the rate at which a thermal gradient relaxes.

Units: m^2/s Symbol: α

Use: The thermal diffusivity is required for calculating rates of heat transfer in unsteady conditions.

Timbers (1975) measured the thermal diffusivity of Echo rapeseed at moisture contents from 3.8 to 9.7% w.b. over a temperature range of 25 to 90°C and found a corresponding increase from 9.5×10^{-8} to 10.8×10^{-8} m^2/s. No difference was found for three other cultivars. A correlation was presented which, converted to SI units, was

$$\alpha = 8.78 + 0.217W \qquad 3.14$$

Results are given in Table 3.2

Moysey et al. (1977) made five replicate measurements of thermal diffusivity at moistures from 0.75% to 19.6% w.b. and temperatures from 25.6 to 19.4°C. Values at and above -4.4°C are given in (Table 3.1). No differences were found between two varieties used. At temperatures above 0°C, values ranged from 9.06 to 10.14 x 10^{-8} m^2/s, very similar to those of Timbers. ASAE D243.2 does not give a correlation for wheat but tabulated values for wheat reduce from 9.26 to 8.0 x 10^{-8} m^2/s as moisture increases from 0.7 to 20.3% w.b. These values exhibit a trend with moisture which is opposite of that shown by Timbers' data for rapeseed.

3.1.4. Net heat of desorption

Definition: The net heat of desorption is the difference between the quantity of heat needed to vaporise unit mass of moisture which is absorbed in a substance, and the quantity of heat needed to vaporise unit mass of free water.

Units: J/kg Symbol: none approved

Use: The net heat of desorption is required to calculate the energy input needed to evaporate moisture from hygroscopic material such as rapeseed.

The net heat of desorption can be derived from the moisture equilibrium properties of the material (reviewed in Section 2.3). Hunter (1987) developed an equation for net heat of desorption for which he evaluated coefficients for rapeseed using data of Pixton and Henderson (1981). Hunter's equation for net heat of desorption of rapeseed can be written as

$$\Delta_a - \Delta_f = \Delta_f \left[\frac{-0.230 \ln(10.59W) + 0.01706(11.91W)^{7.336} \ln(2.446)(W)}{1 - (11.91W)^{7.336}} \right] \qquad 3.15$$

The value of Δ_f is tabulated against temperature in many references, e.g. IHVE (1970). The equation from which Eqn. 3.15 is derived is a very good fit to Pixton and Henderson's (1981) data so Eqn. 3.15 should be suitable for calculating net heat of desorption over at least the range of the data, namely 5 - 35°C and 4 to 18% w.b. moisture.

No other work on net heat of desorption could be found for rapeseed.

3.1.5. Surface heat transfer coefficient

Definition: The surface heat transfer coefficient is the heat flow rate, in this case between seed and air, per unit temperature difference and unit area.

Units: $W/(m^2 K)$ Symbol: h

Use: The surface heat transfer coefficient is used to calculate the heat flow into or out of the surface of the crop material given the temperature difference between the crop surface and the surrounding medium, generally air in this case.

No measured data on rapeseed could be found in the literature. However, it would be possible to calculate values for rapeseed based on general correlations for particulate materials such as that of Gamson et al. (1943).
The validity of such calculated values should, however, be checked by experiment before general use.

3.1.6. Drying coefficient

Definition: The drying coefficient is the ratio of the drying rate of a single particle or thin layer of particles to the difference between the equilibrium moisture of the particles at the prevailing air condition and the actual particle moisture. By definition then

$$\frac{dM}{dt} = -k(M - M_e) \qquad 3.16$$

or, in integral form,

$$R_M = \exp(-kt) \qquad 3.17$$

Units: min^{-1} Symbol: k

Use: The drying coefficient characterises the rate at which the particles lose moisture at a given moisture and air condition, and is therefore fundamental to drying calculations.

Because rapeseed is a porous hygroscopic material, its drying behaviour is mainly in the falling rate region (Patil and Ward, 1989), i.e. the rate of drying is limited by the rate at which moisture is able to migrate through the seed to the evaporation site.

Only in very moist rapeseed would there be any constant rate drying, where the air speed at the surface would be the limiting factor. As moisture diffusivity is strongly temperature dependent, it is important to quantify the relationship between drying coefficient and particle temperature. Therefore, the drying studies of most interest are those which report the rate of drying of the particles exposed to an excess of air supplied at constant conditions, so that the maximum rate of drying is revealed. Using such data the drying of large bulks in complex driers can be computed whereas it is very difficult to do the reverse, i.e. calculate the limiting drying rate of the seeds from data on deep beds.

Kreyger (1972) gives data for the drying rate of rapeseed relative to other common seeds in terms of the rate of loss of moisture per unit time and per degree wet bulb depression.

At the same m.c. as wheat, 20% w.b., the drying rate of rapeseed by Kreyger's definition is ten times higher. The drying rates are both reported to be 0.05% w.b./(°C h) at 6.5% w.b. for rapeseed and 15.0% for wheat. These relationships only apply between 25 - 35°C with air in excess quantity drying seeds in thin layers. The oil-free moisture equivalent of 6.5% w.b. is approximately 13% which shows that, if the mass of the oil is ignored, the moisture for the same drying rate is only a little lower than that of wheat. This difference arises because of the smaller size of the particles.

Patil and Ward (1989) measured the drying rate of thin layers of rapeseed re-moistened to initial moistures of 20.0, 15.4 and 12.1% w.b. using air at temperatures of 30, 40, 50 and 60°C and at velocities of 0.21, 0.33 and 0.53 m/s. Drying was continued until the seed reached moisture equilibrium with the air. No significant effect of air velocity was observed showing that, apart from during the very early stages, the drying rate was

not limited by the air but by diffusion of moisture within the seed. Data, presented graphically, followed the expected pattern, i.e. drying rate increased with air temperature and initial moisture. The results, however, were correlated by an unsatisfactory equation in which the coefficients were given as functions of air velocity, as well as air temperature and particle moisture. Had the part of the curve influenced by air velocity and the air velocity term in the correlation been omitted, the results would have been more generally useful for reasons already explained. The data presented appear to be good quality and could be re-analysed. Data at Silsoe have been recorded on apparatus developed by Bruce and Sykes (1983) at 19 conditions over a range of temperature from 40 - 175°C and of relative humidity from 2 - 70%. These data have not yet been analysed, but they are known to be of high quality and would enable Patil and Ward's data to be checked.

Drying seed in a shallow, fluidised bed is similar to drying in thin static layers in that an excess of air is present. Ghaly and Sutherland (1982) used a drier of this type with air at temperatures of 40 - 70°C to dry re-wetted rapeseed from initial moistures of 12, 14 and 16% w.b. for 8 h, i.e. not to moisture equilibrium. An equation due to Page (1949), Eqn. 3.18, a modified form of Eqn. 3.17, was used to correlate the moisture, M, at any given time, t.

$$R_M = \exp(-kt^n) \qquad 3.18$$

This equation is simple to use but does not describe well the whole drying curve because it does not, for example, represent well enough the reduction in drying rate with time exhibited as equilibrium moisture is approached (Bruce, 1984, for barley). This is confirmed also to be the case for rapeseed by the fact that values for k for the 2, 4 and all 8 hours of drying given by Ghaly and Sutherland differed significantly. For the 60°C case for example, k fell from 2.0 through 1.2 to 0.7. Unfortunately no data were given in tabular or graphical form, so very little useful information on rapeseed drying rates could be extracted from the paper.

Otten et al. (1989) dried thin layers of rapeseed from 15% w.b. moisture at only two air conditions; temperature of 30°C at relative humidity of 60% and 40°C at 40%. Five replicate tests were done at each condition, each of 4 h duration. Eqn. 3.18 was used to describe the data but, as only two conditions were available, it was not possible to derive a general relationship for the effect of air condition on the parameters of Eqn.3.18. The parameters given were k = 0.0188 and n = 0.824 for 30°C and 60%, and k = 0.0426 and n = 0.670 for 40°C and 40%. The limited data would be useful for comparing with the predictions of a general model but are otherwise of little use.

Sokhansanj et al. (1984a) measured the drying rates of rapeseed over several cycles of rewetting and drying. Thin layers of crop, initially naturally moist, were dried with an excess of air at a temperature of 70°C, from an initial moisture of 15.0% to a final moisture of 10.0% wet basis, i.e. not to equilibrium with the air, which would have been around 2.5% w.b. The crop was rewetted and dried again in the same way. No data or graphs were given. Eqn.3.18 was fitted to each curve and the coefficients were compared to determine if the drying behaviour had changed as a result of successive rewetting and drying.

The three replicate drying curves for naturally moist rapeseed were described by

$$R_M = \exp\ (-0.183t^{0.572}) \qquad 3.19$$

Drying rate of rapeseed decreased as a result of each successive re-wetting and drying cycle unlike wheat and barley which showed no significant change. The usefulness of this study for general purposes is limited

by several points: the limited moisture range, 5%, over which the seed was dried; the final moisture, 10% w.b., which is too high for safe storage; and the single value of air temperature used.

To measure the rate at which the seed absorbed moisture, Shatadal et al. (1989) used samples of rapeseed exposed in thin layers to humid air . This information would be of use for calculationing the response of seed to processes in which it was exposed to humid air. Two levels of relative humidity, 80 and 90%, and four of temperature 7.5, 15.0, 22.5 and 30.0 °C were used, though the two lowest temperature conditions could not be reached at 90% r.h. Tests were replicated three times and were continued until moisture equilibrium was reached. Eqn. 3.20 was used to correlate the data

$$R_M = \exp\ (-kt^{0.818}) \qquad 3.20$$

where k was given as a function of temperature and relative humidity as

$$k = -0.0257 + 0.00094T + 0.000314\ \varphi \qquad 3.21$$

No data were tabulated, though values for k and the time exponent were given for all the drying test conditions. Use of relative humidity, φ, in Eqn. 3.21 the expression for k is disappointing because the effect of relative humidity is best accounted for by its influence on the equilibrium moisture which the seed is approaching rather than on the rate of approach to that equilibrium. This is because unlike the air temperature, the r.h. cannot influence the conditions inside the seed. The need to include r.h. in the equation for k suggests that either true equilibrium had not been achieved when the tests were ended or that some other interaction, perhaps between r.h. and temperature, had occurred in the equipment.

In calculations of drying it is normally assumed that the same rate of approach to equilibrium occurs whether that equilibrium is below (drying) or above (re-wetting) the current moisture of the seed. Shatadal et al. did not make a comparison of the values of k for rewetting with those of other workers for drying.

3.1.7. Resistance to airflow

In the design of crop drying systems the selection of the correct design and size of fan(s) is crucial. In a well-designed clean system the pressure required to generate the correct airflow through the crop is largely a result of the resistance of the crop itself rather than of the perforated ducts or friction losses. Therefore the pressure-airflow relationship for the crop bed must be known if crop drying systems are to be correctly designed.

A reasonable amount of work was found on this subject for linear flow of air through static beds of rapeseed but only one reference gave a formula relating pressure to airflow in other configurations such as radial flow bins, flow out of ducts and across round bins. No details were found for moving beds.

Much of the recent work is from Canada where Jayas has carried out a comprehensive study reported in several papers. Working with two varieties, Jayas et al. (1987a) measured the pressure generated across a bed of rapeseed filled by "sprinkle" fill which gave a dense bed, and "spout" fill which resulted in a less dense bed. Like other workers he found a linear effect of depth on pressure, which means that doubling the depth of the bed will require double the pressure drop across the crop to achieve the same air velocity through the bed.

Jayas used air speeds from 0.0004 to 0.7584 m/s which covers the range from low volume ventilation to more than fluidisation velocity. He correlated the data using an equation due to Shedd (1953)

$$v = A(\Delta P)^B \qquad 3.22$$

where v = air speed, m/s
ΔP = pressure drop per unit bed depth, Pa/m
A,B = coefficients determined from experimental data

His data agreed closely with that obtained over a more limited range of airflow by Friesen et al. (1982) and by Lawton (1965). Values for A and B in Eqn.3.22, determined by Jayas, were given for three values of m.c. of *B. Campestris*, Tobin variety, viz. 6.5, 10.3 and 14.5% wet basis and one of *B. Napus*, Westar, viz. 7.0%, for spout and sprinkle fill. The range of values of B was small so a single value was considered acceptable for each airflow range. The value of coefficient A was described by the following relationship which means that the pressure needed for a given air velocity is reduced as moisture increases.

$$A = (C + D.W) \times 10^{-6} \qquad 3.23$$

The coefficients for spout filled Tobin rapeseed were as given in Table 3.4.

Table 3.4

The effect of air velocity on coefficients of Eqns 3.22 and 3.23 (from Jayas et al. 1987a)

Coefficient	Air speed, m/s		
	0.0004-0.02	0.02 - 0.7584	0.0004 - 0.7584
B	1.457	0.843	1.054
C	11.51	90.39	54.54
D	0.337	21.15	1.44

The effect of method of fill was very significant, the sprinkle-filled, and therefore more dense, beds giving, for the same air speed, an average of 2.2 times the pressure drop obtained by spout filling. This is a little higher than the multiplier of 1.5 for pressure drop for a given air speed in spreader-filled seed compared to spout-filled seed given by ASAE (1984). Seed size was also important: the larger seeds of Westar (*B. Napus* 1.8 mm diameter), gave 0.6 times the pressure drop of the smaller-seeded Tobin (*B. campestris*, 1.5 mm diameter) for the same air speed.

Jayas and Muir (1991) also explored the effect on the relationship between pressure and air speed of the amount of fine material and chaff in the sample. Samples ranging from 100 to 50% clean seed, with the remaining fraction being varied between all chaff and all fines, were packed both loosely and densely. Coefficients for Shedd's equation, Eqn. 3.22, were calculated for the same two airflow ranges as in Jayas et al. (1987). The following relationship for A in Eqn. 3.22 was presented as a function of the mass percentage of clean seed, E_s, chaff, E_c, and fines, E_F.

$$A = x_1 E_s + x_2 E_c + x_3 E_F \qquad 3.24$$

Values of x_1 - x_3 are given in Table 3.5.

B in Eqn. (3.22) was found by Jayas and Muir (1991) to be almost independent of method of fill, and to have values of 0.83 for V = 0.02 - 0.758 m/s, and 1.44 for V = 0.004 - 0.02 m/s.

Table 3.5
Coefficients of Eqn. 3.24 for two ranges of air velocity and two packing methods

Coefficient	Air velocity, m/s	
	0.0004 - 0.02	0.02 - 0.758
	Loose fill, 700 kg/m^3	
x_1	13.33	313.1
x_2	129.8	1525
x_3	-10.90	-209.7
	Dense fill, 775 kg/m^3	
x_1	4.78	194.1
x_2	7.19	226.8
x_3	-5.04	-246.2

Jayas et al (1987b) experimented with horizontal and vertical airflow through beds of rapeseed and found, surprisingly for a near-spherical seed, that the resistances were significantly different. Within the range of air velocities used, 0.0158 to 0.171 m/s, the coefficient A in Eqn. 3.22 applied to horizontal flow was given by multiplying the coefficient for vertical (Eqn. 3.24 with coefficients from Table 3.5) flow from Jayas et al. (1987a) by 1.7, i.e. the resistance was much less in the horizontal direction than in the vertical. This difference was present for both spout and sprinkle fill, and was similar in magnitude to the difference for wheat found by Kumar and Muir (1986).

The data forming the basis of these studies is from Jayas' (1987) PhD thesis. No original data or even graphs are given in Jayas' papers but some of the data has been published by Singh# and Sokhansanj (1984).

Patil and Ward (1988) used six levels of moisture and a limited range of air speed range, suitable for drying, of 0.17 - 0.32 m/s. As seed moisture increased, bulk density was observed to reduce, and therefore pressure drop reduced for a given air speed. The authors used Shedd's Equation 3.22, to describe their data. Values of A and B were given (Table 3.6) for each moisture value but no relationship for A or B as a function of moisture was developed.

Footnote: Singh is the former name of D S Jayas

Table 3.6
Coefficients in Eqn.3.22 due to Patil and Ward (1988)

Moisture content, % w.b.	Coefficient, A	Coefficient, B
19.6	0.176	0.626
17.6	0.169	0.620
15.5	0.163	0.631
11.9	0.148	0.627
8.83	0.147	0.613
6.46	0.142	0.606

A relationship was developed by multiple linear regression for pressure drop as a function of moisture content and air speed,

$$\Delta P = -0.354 - 0.067W + 13.72v \qquad 3.25$$

but this is of a purely empirical form and is therefore unlikely to behave well outside the range of data of Patil and Ward.

Burrell and Armitage provided data in a personal communication to Muir and Sinha (1986) who fitted coefficients to an inverted form of Eqn. 3.22 namely

$$\Delta P = qv^s \qquad 3.26$$

Burrell and Armitage had subjected rapeseed at 8% w.b. moisture and 690 kg/m^3 density to air speeds over the range 0.01 to 0.315 m/s. Muir and Sinha presented their equation as

$$\Delta P = 11633v^{1.237} \qquad 3.27$$

Mathies and Petersen (1974) fitted Eqn.3.26 to their data for spring rape, and found $q = 1.66 \times 10^4$ Pa/m and $s = 1.14$. The same Eqn. was used by Nellist and Rees (1967) for winter rape at 18% moisture content which would be expected to contain larger seeds than the spring rape at 8% w.b. moisture used by Matthies and Petersen, and therefore to have lower resistance. This was the case, the coefficient found by Nellist and Rees being $q = 9.78 \times 10^3$ Pa/m and $s = 1.26$.

Sutherland and Ghaly (1982) used Eqn.3.28 due to Ergun (1952) to correlate their data (not given in their paper) obtained using air speeds up to 0.4 m/s through clean seed at 706 kg/m^3 density and 5.7% m.c.

$$\Delta P = a\mu v + b\rho_b v^2 \qquad 3.28$$

Eqn. 3.28 has the advantage over Eqns. 3.23 and 3.26 in that, while expressing the curvature of the data, it can be fitted in the linear form, Eqn. 3.29, without introducing logarithms

$$\Delta P/v = a\mu + b\rho_b v \qquad 3.29$$

Values of a and b were given by Sutherland and Ghaly as 39.21×10^4 and 11.68 respectively. Compared with wheat the pressure drops at a given air speed ranged from a factor of 1.9 higher at air speeds below 0.1 m/s to 1.75 higher at speeds of 0.4 m/s. The influence of air temperature from 20 - 60°C was found to be negligibly small.

ISO Standard 4174 (1980) gives the following equation for expressing pressure drop as a function of airspeed for one-dimensional flow of air through laboratory samples of grains.

$$\Delta P = Av + Bv^2 \qquad 3.30$$

Only one paper (Hunter, 1983) was found which actually made use of this relationship so its inclusion in a Standard seems premature. Ergun's (1952) equation, Eqn. 3.28 is of the same form and has a sounder basis so it would seem to be preferable to the purely empirical Eqn. 3.30. Hunter (1983) used Shedd's (1953) data to derive coefficients for Eqn. 3.30 for 27 different seed types. For rapeseed, of Tower variety at 5.7% w.b. he reported A = 7097 Pa s m^{-2} and B = 13900 Pa s^2 m^{-3}.

The reader interested in further details of equations for resistance to airflow is referred to Alagusanderam and Jayas (1990) who reviewed the many forms of equation used to model the relationship between pressure and velocity for crops generally.

Measurements of pressure in the case of parallel airflow can be used to predict the pressures or airflows in more complex cases such as two or three dimensions. For simple, geometrical flows such as radial or conical flow, this can be achieved by mathematical analysis from the parallel flow case. For example Sutherland and Ghaly (1982) integrated the Ergun's equation, Eqn. 3.28, to provide an expression for the non-linear, divergent air flow in radially ventilated bins, though the equation was not validated in their work. The equation is

$$P = AQ + BQ^2 \qquad 3.31$$

where

$$A = \frac{a\mu}{2\pi} \log_e \left(\frac{r_o}{r_i}\right) \qquad 3.32$$

and

$$B = \frac{b\rho}{4\pi^2} \left(\frac{1}{r_i} - \frac{1}{r_o}\right) \qquad 3.33$$

where a, b, ρ and μ are as for Eqn. 3.28.

Hunter (1983) derived expressions for common configurations of seed bulk and aeration duct shape from Eqn. 3.30. These bulks are all on flat floors, but the ducts may be on-floor or under-floor to give substantially vertical flows, or vertical, on-wall types to give horizontal flow. The expressions are complex to solve but could be handled by a programmable calculator.

For more irregular shapes or where the anisotropic nature of airflow resistance is to be accounted for, numerical techniques are required to solve equations for pressure and flow.. Jayas et al. (1990) developed a model to predict the airflow in an axisymmetric bin of rapeseed given external pressures and the bin geometry. Their bin was cylindrical, ventilated through a perforated floor and partially filled with seed from a central point so that a conical surface formed. The model was solved using the finite element method, and the predicted pressures at several locations within the bed were compared with measurements of pressure made on a bin of 4.6 m diameter. Predicted pressures were reported as within 6% of measurements at most locations in the bin. This technique could be used to predict the overall airflow in bins of various configurations and to highlight the low airflow regions of irregularly shaped beds, but the model presented

by Jayas et al. (1990) does not cope with non-axisymmetrical cases such as a bin filled from one side, a rectangular bin or ventilation from a floor which is not fully perforated. An extension to the model so that the effects of drying on the crop resistance and hence on the air flow could be taken into account would be a major advance.

Friesen and Huminicki (1986) measured pressure drops through beds of grains, including rapeseed, during 14 tests on fully perforated ventilated floors on farms. Airspeed ranged from 0.012 to 0.077 m/s. No data values were given but Eqn. 3.34 was used to summarise the data. The exponent, 1.05, is so close to unity that the relationship between pressure and airspeed was almost linear.

$$\Delta P = 9181\ v^{1.05} \qquad 3.34$$

For floors which are 50% perforated material or less, an equation was given to calculate the increase in pressure drop for wheat but none is given for rapeseed and, in any case, the form of the equation is not sound. The pressure loss caused by the perforated rapeseed-type flooring was said to be negligible up to an airspeed of 0.075 m/s, calculated as an average over the floor.

All of the above work was done on static beds of seed. No information was found on the pressure - airflow relationship for moving beds of rapeseed which, because of dilation, would be expected to be lower than in static beds of the same depth.

No data was found on the increase in resistance which is known to occur when a certain amount of deterioration has occurred due to mould and the rapeseed has started to 'cake', and which, by reducing airflow, accelerates the deterioration.

3.2 Biological

3.2.1 Safe temperature for drying with heated air

Clearly, rapeseed destined for sowing must be dried at temperatures below those likely to cause any reduction in seed viability. Whilst, in the immediate short term, the loss of seed viability may not affect oil quality, in the longer term the oil in dead seeds will increase in free fatty acid content and peroxide value. Such oxidative changes also tend to be accompanied by a darkening in oil colour (Ghaly & Sutherland, 1984). Conversely drying immature seed at 80°C, a temperature which causes damage to germination, can reduce the number of green seeds in immature seed lots and this destruction of chlorophyll improves the colour of the extracted oil (Cenkowski et al. 1989). However, this conclusion was reached on oil extracted immediately after drying. There do not appear to have been any studies of the effect of initial drying treatment on subsequent deterioration of oil quality during prolonged storage, although it has been shown that normal dry rapeseed deteriorates in store more rapidly than barley (Sinha & Wallace, 1977).

3.2.1.1 Heating without drying

The extent of any loss of viability during drying is a function of the seed moisture content, its temperature and the time for which various temperature and moisture combinations are experienced. In a real dryer, these combinations of variables are very complex so that studies to define safe temperatures have tended to consider the drying of seeds in shallow and thin layers under controllable laboratory conditions. Even here the variation of moisture with time increases the complexity. A simplification, or reduction in the variables, is given by a technique which was originally developed in work on seed storage (Roberts, 1960)

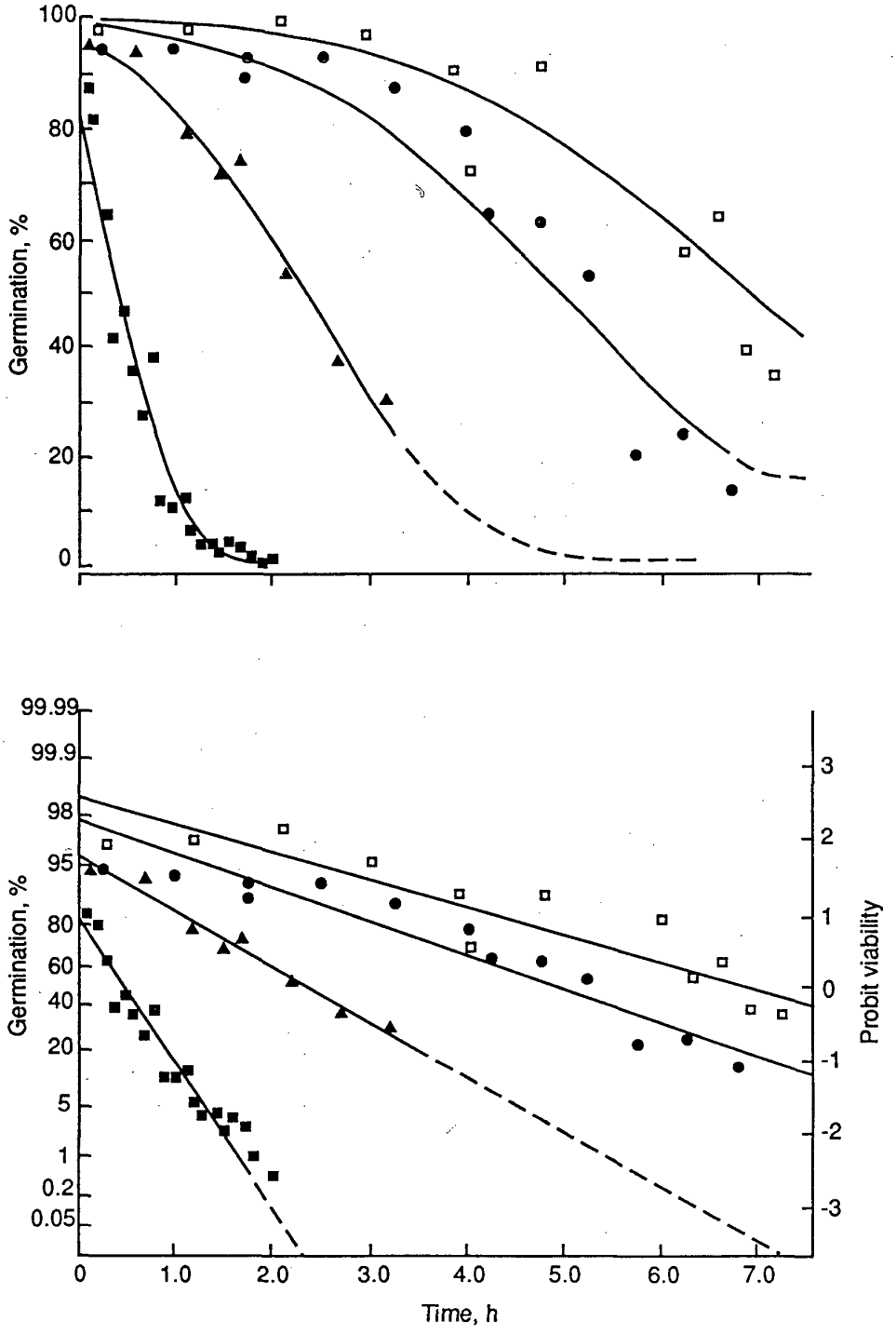

Fig.3.1 Effect of exposure time on the germination of wheat grains heated without evaporation at 60°C and at moisture contents of 22.1 (■), 20.2 (▲), 18.1 (●) and 16.8 (□) % w.b. plotted on linear (top) and probability (bottom) scales. Lines fitted by 'probit' model, Eqn. 3.36 (source: Nellist & Bruce, 1987).

and applied to heated-air drying of cereals by Nellist (1981). This is to study the rate of viability loss under conditions of constant moisture content and temperature. These conditions are achieved by holding the seeds at the required temperatures in sealed containers in which evaporation is not possible. Although one of us (MEN) has some unpublished data of this type for rapeseed, the only published work we have found is that of Ellis et al. (1989).

At this point it is necessary to explain that in storage, seed loses viability as a natural consequence of ageing and that under stable conditions of temperature and moisture the deaths of the seeds in time are 'normally distributed'. That is to say that, initially, the decline in germination is slow but, as more seeds die, the rate of death tends to increase until, when half the seeds are dead, it must inevitably decline and reach a very low value as the last few very long-lived seeds approach death. A plot of the decline of germination in time which represents the integral of the death rate, therefore tends to have a sigmoid shape (Fig.3.1(top)) characteristic of the normal probability integral. Thus if we plot germination against time on probability graph paper (Fig.3.1 (bottom)) the sigmoid curves are transformed to straight lines. Mathematically we can represent this transformation as:

$$G = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{X = (t-\bar{t})/\sigma} \exp(-\tfrac{1}{2}X^2)dX \qquad 3.36$$

where G = germination expressed as a decimal

t = exposure time

$\bar{t}$ = the exposure time at which G = 0.5 (50% germination) i.e. the half life of the seed sample

and σ = the standard deviation of the distribution.

The quantity X is a value termed the standard normal deviate which is symmetrical about zero at the point G = 0.5 (i.e. $\bar{t} = t$). X depends on $\bar{t}$, t and σ but for any value of X there is only one value of G. Also X varies linearly with t. Thus if we substitute X for G the abscissa of the plot as in Fig. 3.1 (bottom) then we have straight lines. These can be described by Eqn. 3.37 (Fig.3.2).

$$X = X_o - t/\sigma \qquad 3.37$$

A branch of statistical analysis called 'probit' analysis (Finney, 1971) is based upon Equations 3.36 and 3.37. Ellis and Roberts (1980) have coined the term 'probit viability' to describe values of X. X_o, the initial value at t = 0, is their constant K_i. The standard deviation, σ, is a measure of the dispersion of the deaths about the mean drying time (or half life) and can be shown to be that time in which the germination reduces from 83.1% to 50%.

The significance of the linearity of Eqn 3.36 is that in 'probit' units, the death rate $1/\sigma$ is constant for a given environment and can be expressed as a function of seed moisture content and temperature. Since σ is dependent only on the environment and not upon the initial quality of the seed (Ellis & Roberts, 1981), it is possible to add reductions in 'probit' from successive environments experienced by the seed to estimate a total loss. The final 'probit' viability can be estimated by subtracting the accumulated probit loss from the initial 'probit' value. Conversion of the final 'probit' value to germination units gives the final viability. The procedure is similar to using logarithms.

By applying this approach to predict the cumulative loss of germination in wheat grain passing through a cross-flow drier, Nellist and Bruce (1987) were able to construct a chart showing the safe drying temperatures for such a drier at a range of initial and final moisture constants.

So far the only published values of σ for rapeseed (*Brassica napus*) are those given by Ellis et al. (1989) which are confined to the single temperature, 65°C. Their data were fitted by equation 3.38.

$$\sigma = 60 \exp (11.375 - 4.54 \ln W) \qquad 3.38$$

where σ = inverse death rate, min/probit unit
W = moisture content, % w.b.

The initial value of X_o in Eqn. 3.37 derived from the curve-fitting was 1.98, equivalent to an initial germination of 97.6%. Without any information of the effect of temperature on σ it is not possible to use equations 3.37 and 3.38 to estimate safe drying temperatures under drying conditions but it is possible to make a comparison of the sensitivity to heat damage with wheat. Nellist and Bruce (1987) give an equation for the death rate of wheat which, for the temperature, 65°C, can be reduced to Eqn 3.39.

$$\sigma = 60 \exp(15.538 - 5.90 \ln W) \qquad 3.39$$

Evaluating Eqn. (3.38) and (3.39) over a range of moisture contents and calculating exposure times for loss of probit equivalent to a reduction in germination of 2% from an initial 98% we can plot the curves of Fig.3.3. These show that for a given moisture content in the range below about 18%, rapeseed loses germination more rapidly than wheat. However, the difference in sensitivity is not quite as might appear because, as discussed elsewhere in this review, the moisture constant range over which rapeseed is dried is lower than that for wheat. Thus wheat at 14% m.c.w.b., a normal final moisture content, is calculated to reduce to 96% in 1/3 h whereas even at 10%, which is a high value of final moisture, rapeseed requires 3/4 h. So safe drying temperatures are not necessarily any lower than those for wheat. However, they cannot properly be evaluated without further information on the effect of temperature on the death rate.

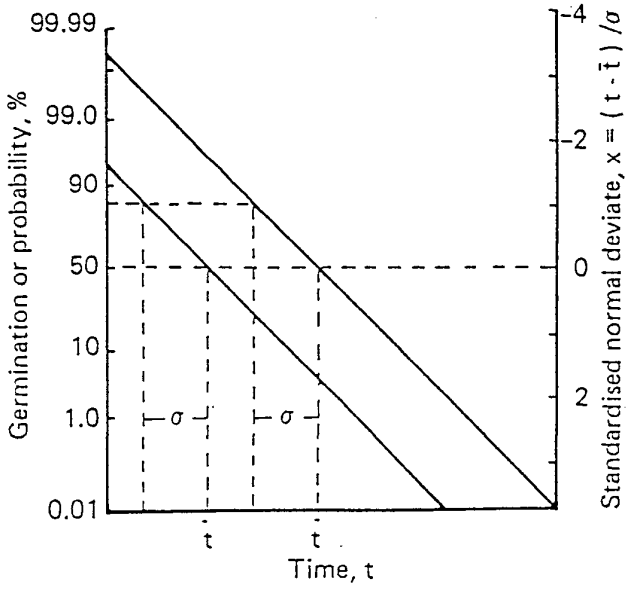

Fig.3.2 Representation of the normal distribution of seed deaths as a 'probit' scale to give a linear relationship with time. (Source: Nellist, 1981).

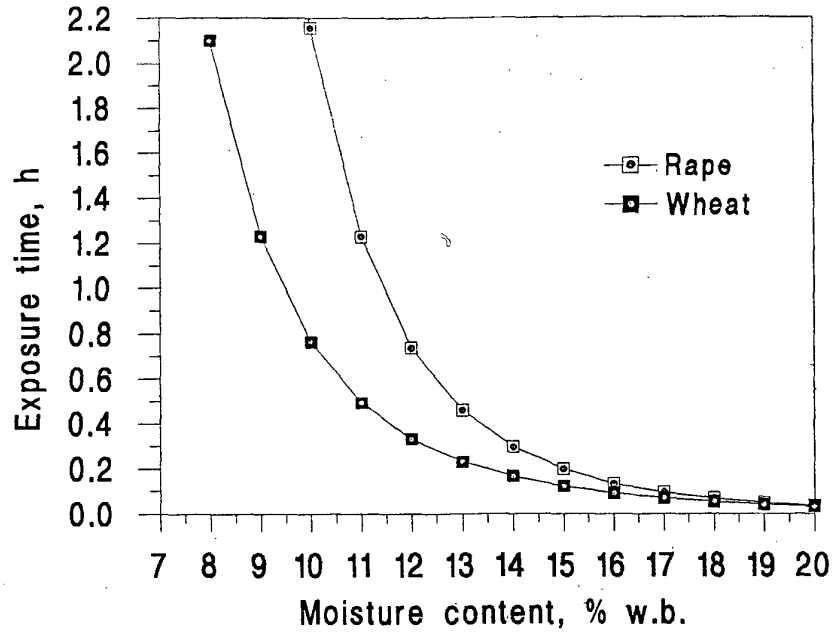

Fig.3.3 Effect of moisture content on the time of exposure reducing the viability of rape and wheat seeds from 98 to 96% when heated without evaporation at 65°C.

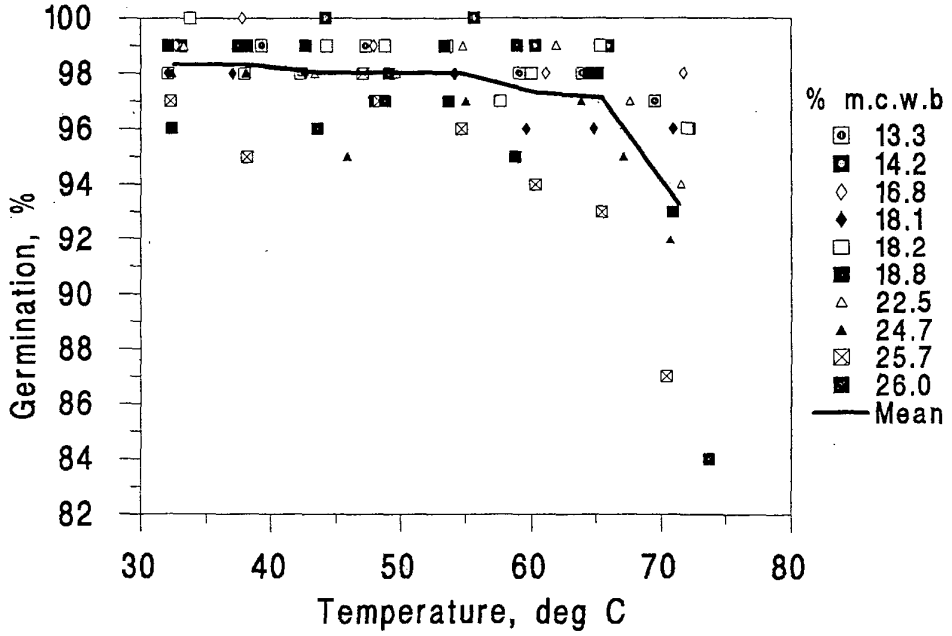

Fig.3.4 Effect of initial moisture content and drying air temperature on the germination of rapeseeds dried in beds 150 mm deep. (Source: Nellist, et al. 1970)

3.2.1.2 Heating with evaporation - drying

In the meantime, some rough guidelines can be drawn from drying experiments conducted in thin and shallow layers. Woodforde and Lawton (1965) rewetted rapeseed to 20% m.c.w.b. and dried thin layers for 1 hour at temperatures from 40 to 85°C. Depression in germination was marginal at 65°C but clearly occurred at 70°C and above. They concluded that 60°C would be a safe limit.

Nellist et al. (1970) dried samples of the winter rape Viktor, an old high-erucic variety, which had been harvested both directly from standing crop and from windrow. Moisture contents ranged from 13.3 to 26.0% w.b. Samples were dried in beds 150 mm deep ventilated with air at a mass flow of 9.3 kg air. kg seed^{-1}h^{-1} and air temperatures from 32 to 74°C. Drying times ranged from 0.7 to 7.5 h and the plotted drying curves indicated that for the majority of the treatment time, the drying zones remained within the bed. This means that the seed treatment will have varied significantly from top to bottom of the bed but that the treatment of the bed overall, and hence the quality of the dried seed when mixed, was not unrepresentative of conditions in a majority of real dryers. The results are plotted in Fig. 3.4. They are quite variable but statistical analysis confirmed a depression in germination at the nominal air temperature of 70°C and that this depression was associated with the wetter seed. Essentially, there was no evidence of any damage at initial moisture contents below 18%. It was largely as a result of this work, that the MAFF recommended safe drying temperatures were prescribed as follows (MAFF, 1982):

Moisture content % wet basis	Maximum safe grain temperature, °C
Below 17	65
19	60
21	55
23	49
25	43
27	38
29	32

In similar work drying the Canadian cultivar, Echo, in beds 250 mm deep, McKnight and Moysey (1973) found depression of germination at temperatures greater than 60°C to an extent dependent upon moisture content. They state that 'a drying air temperature of 160°F (71°C) will cause neglible reduction in viability if the initial moisture content is 11 percent. For each 2% increase in moisture above this level, the drying air temperature should be reduced by 10°F (5.5°C)'. Thus their temperatures are:

Moisture content, % w.b.	Maximum safe drying air temperature, °C
11	71
13	66
15	66
17	54
19	49
21	43

These recommendations are more conservative at the higher moisture contents than those of the MAFF guidelines and detailed experimental results are not given. Sutherland and Ghaly (1982) dried seed of the cultivar Tower conditioned to initial moisture contents of 12, 14 and 16% w.b. in a fluidised bed using inlet air temperatures of 40, 50, 60, 65 and 70°C. The fluid bed treatment is similar to thin layer drying and these experiments were similar to those of Woodforde and Lawton (1965) except that in every case the drying time was 8 h so that the seed was overdried to final moisture contents ranging from 4.8 to 1.2% w.b. These results (Table 3.7) show that no loss in germination occurred at temperatures up to 60°C; a small loss occurred at 65°C and a substantial loss occurred at 70°C particularly at the two higher moisture contents. Seed at 12% initially was completely killed by a temperature of 75°C.

In Fig.3.5 both these results and those of Woodforde and Lawton (1965) are plotted for comparison with those of Nellist et al. (1970). The graph shows that the freshly-harvested seed used by Nellist et al. had a higher initial viability than the rewetted seeds used in the other two studies and that probably because of this, the depression in germination at the higher temperatures was greater in the initially poorer seed. This accords with the 'probit' hypothesis. It is interesting that there is good agreement between the results of Sutherland & Ghaly and Woodforde and Lawton, even though the drying times were widely different. In a subsidiary experiment in which drying time was varied, Sutherland and Ghaly found that most of the damage caused at 70°C occurred with the first hour of drying and that further exposure caused little extra damage. This explains why the long drying times had little extra effect and again accords with the 'probit' hypothesis.

Overall these drying experiments support the conclusion that no detectable reduction in rapeseed viability is likely to result from drying air temperatures up to 60°C. An interaction between drying air temperature and moisture content exists but has not been clearly defined. It would be possible to use these results to derive coefficients describing the 'probit' death rate but such an exercise is outside the scope of this review.

As a general guide, there seems no reason to alter present Ministry recommendations for safe temperatures to preserve viability. Insofar as safe drying temperatures are dependent upon the specific design of dryer, it may be considered that it is the dryer manufacturer's responsibility to specify safe temperatures for his particular machine. As far as one can tell, such recommendations are based upon accumulated experience rather than upon any systematic scientific study.

As for the direct effect of heated-air drying on oil quality, Nellist et al. (1970) found no effect on free fatty acid content, peroxide value or chlorophyll content at drying temperatures up to 71°C and McKnight and Moysey (1973) suggest that temperatures up to 93°C do not affect oil quality. In their fluidised bed experiments Sutherland and Ghaly (1982) found no increase in FFA and peroxide value at temperatures up to 75°C for seed at 12% m.c.w.b. and 70°C for 14 and 16% m.c.w.b. However, they did note a slight darkening of the oil extracted from rapeseed heated to 75°C. MAFF (1982) do not make a separate recommendation for safe temperatures for oil quality.

Table 3.7

Effect of drying air temperature on germination, free fatty acid percentage and oil colour of three samples of rapeseed dried in a fluidised bed dryer (adapted from Sutherland and Ghaly, 1982)

Bed temperature (°C)	Moisture content (% w.b.)	Germination, %	FFA% oleic acid	Photometric colour	
				Before heat bleach	After heat bleach
Control	12.0	90 (88-93)#	0.46	5.48	5.09
40	3.7	91	0.42	3.58	1.00
50	2.9	93	0.33	3.40	1.10
60	2.1	94	0.34	4.07	1.00
65	1.9	88*	0.40	3.33	1.85
70	1.5	76*	0.39	2.94	1.63
75	1.2	0	0.33	3.23	3.69
Control	14.1	91 (89-93)	0.46	5.22	5.97
40	3.7	96	0.39	3.29	0.57
50	2.7	91	0.37	3.69	0.62
60	2.2	92	0.32	3.23	1.09
65	1.9	85*	0.35	2.75	2.07
70	1.6	34*	0.32	2.46	1.13
Control	16.1	92 (89-95)	0.49	6.48	7.29
40	4.8	92			
50	3.0	94			
60	2.1	91	0.32	3.33	0.61
65	1.8	88*	0.32	2.61	0.92
70	1.4	37*	0.28	3.14	1.61

* Weak seedlings

The numbers in brackets indicate the range of the 3 control values

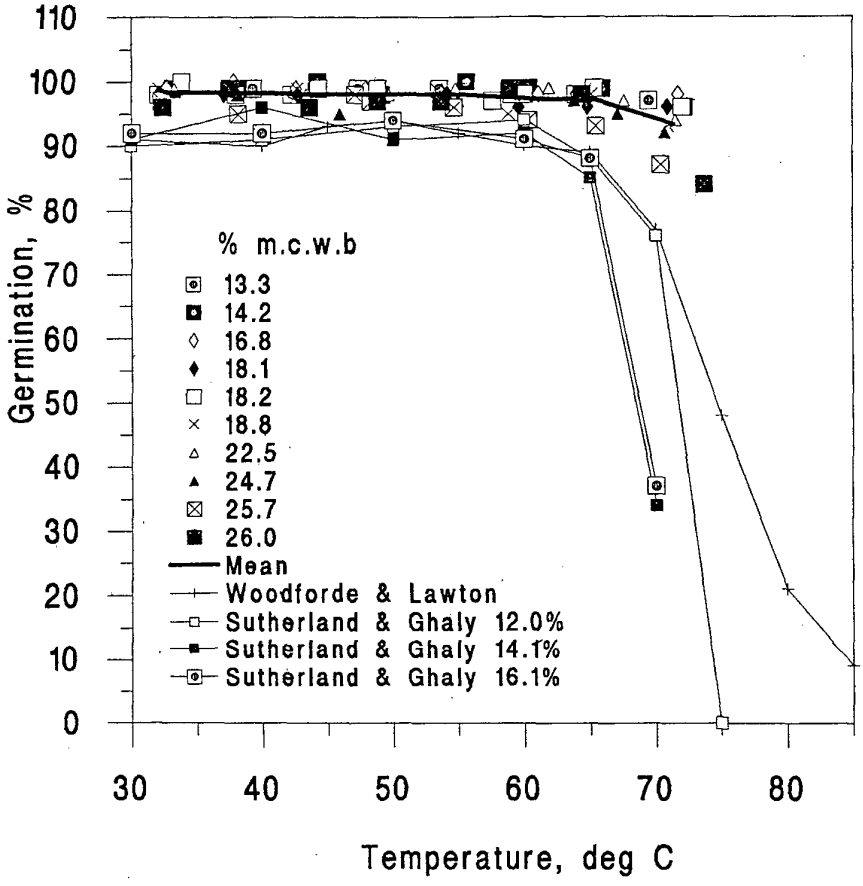

Fig.3.5 Effect of initial moisture content and drying air temperature on the germination of rapeseed. Comparison of the results of Nellist (1970) for 150 mm beds with those of Woodforde and Lawton (1965) for thin layers and of Sutherland and Ghaly (1982) for fluidised beds.

3.2.2 Conditions for short and long term bulk storage

The first threat to the quality of undried, or inadequately dried, rapeseed kept in bulk is the loss of quality through microbial activity. Mould growth is a precursor of heating and mite infestation and, in dry seed, insect activity may cause moisture accumulation and secondary moulding. Thus the appearance of visible mould has long been taken as an indicator of spoilage and is the basis of the most widely used data for the estimation of safe storage life in cereals. Burrell et al. (1980) carried out experiments to determine the time taken for rapeseed to develop surface moulds and confirmed that this occurred before there was any significant loss in germination. Their data for visible mould (Table 3.8), plotted in Fig.3.6, show the importance of reducing seed temperature and seed moisture content in prolonging safe storage life. Burrell et al. found that 'seed clumping' preceded the occurrence of visible mould and was accompanied by a deterioration in seed appearance. They, therefore, suggested it was a better criterion for determining the safe storage period. These times are plotted in Fig.3.7

Table 3.8

Maximum mould-free period (days) of rapeseed stored in tubes (Burrell et al. 1980)

	Initial moisture content	Temperature, °C				
		25	20	15	10	5
(A) Seed 'clumping'	17.0	4	4	6	11	20
	15.6	4	6	6	11	28
	13.7	4	6	11	20	46
	12.3	8	6	18	25	109
	10.6	11	18	42	42	238
	8.9	23	48	116	279	>300
	6.7	69	180	>300	>300	>300
(B) Visible colonies	17.0	5	6	10	18	33
	15.6	6	6	14	19	40
	13.7	7	10	18	31	72
	12.3	10	17	26	54	119
	10.6	21	33	75	119	>300
	8.9	90	119	256	>300	>300
	6.7	>300	>300	>300	>300	>300

Prior to the work of Burrell et al., Kreyger (1972) had presented maximum safe storage times (Table 3.9) based on studies of germination loss and these have formed the basis of advisory recommendations over many years (McLean, 1989). Muir and Sinha (1986) noted that Kreyger's times based on germination studies were very similar to those of Burrell et al. (1982) for the development of visible mould but shorter than those measured under Canadian conditions by Mills and Sinha (1980). However, for reasons of caution, they decided to use Kreyger's times in preference to their own in computer simulated studies to determine airflow rates necessary for bulk storage or near-ambient drying of rapeseed under Canadian conditions. For convenience of use they fitted the data to the exponential equations (3.40) and (3.41). (Muir and Sinha, 1986).

Table 3.9

Maximum safe storage times, days, for the storage of rapeseed without significant loss of germination. (Kreyger, 1972).

Moisture content, % w.b.	Storage temperature, °C				
	25	20	15	10	5
17	0	3.5	7	14	28
14	7	14	28	59.5	119
12	17.5	35	70	147	350
10	35	70	140	350	840
9	63	133	280	630	1400
8	112	224	455	1120	2800
7.5	175	350	700	1820	4200
7	273	560	1190	2800	7000
6.5	378	770	1680	4200	7000

for W < 11% m.c.w.b.

$$\theta = \exp(14.331 - 0.6954W - 0.1589T) \qquad 3.40$$

for W $\geq$ 11% m.c.w.b.

$$\theta = \exp(12.153 - 0.4743W - 0.1451T) \qquad 3.41$$

where θ = maximum allowable storage time, days
W = moisture content, % w.b.
T = temperature, deg.C

The goodness of fit for storage times up to 400 days is shown by Fig.3.8.

These relationships are clearly useful for predicting storage life under conditions of constant moisture content and temperature but they are not so easily applied to situations such as those experienced immediately post-harvest when wet seed undergoes a multiplicity of moisture contents and temperatures as it is dried or conditioned. The equations have been applied, however, by using a 'spoilage index' (Muir and Ingram (1975), Sharp (1982), Metzger and Muir (1983), Bowden et al. (1983). The 'spoilage index' is the sum of the fractions of safe storage times spent at each condition and unacceptable spoilage is deemed to have occurred when this fraction reaches unity.

The problem with the spoilage index is that it does not give an indication of the overall quality of the seed. More importantly, perhaps, it does not give information on the interactive effect of the spoilage processes as they feed back moisture and heat into the seed mass. To estimate these effects it is necessary to quantify the process leading to the spoilage, i.e. microbial activity. The most comprehensive attempt to measure microbial activity in rapeseed and use the data to develop safe storage periods was made by Schmidt and

Jacobson (1982). They measured the rates of oxygen consumption and carbon dioxide production of the cultivars 'Gulliver' and 'Line' at temperatures from 10 to 35°C and moisture contents from 9 to 20% w.b. Respiratory quotients, the ratio of $C0_2$ produced to 0_2 consumed, ranged from 0.3 to 0.71. This contrasts with values close to unity usually obtained for cereal grains. For the consumption of oil or fat during respiration, the quotient should be around 0.7 but their values are generally lower. Schmidt and Jacobsen observed that their respiration rates expressed in mMols of gas/(h tonne of dry matter) increased exponentially with increasing moisture content but linearly with temperature. By expressing their rates per unit of temperature and correcting moisture contents to equilibrium relative humidities, they obtained a straight line plot (Fig.3.9) from which a regression analysis gave Equation (3.42).

$$R = \exp (a + b\,\varphi + \ln T) \qquad 3.42$$

where R = respiration rate, mMols/h/tonne dry matter
T = temperature, °C
φ = relative humidity, %

and coefficients a and b = -16.96 and 0.2277 for oxygen consumption and -17.47 and 0.2252 for carbon dioxide production respectively. Conversion of moisture content to relative humidity was made using equation 3.43 obtained by fitting the desorption data for Tower rapeseed reported by Pixton and Warburton (1977).

$$\varphi = 100.\exp(-18011((1/(273 + T)) - 0.00177)/W^{2.0516} \qquad 3.43$$

Schmidt and Jacobsen then went on to make the assumptions (1) that 0.1% (1 g in 1 kg) loss of dry matter represented the limit of allowable loss and (2) that the respiration was evenly divided between the carbohydrate and the oil. Then since 1 g molecule of oxygen (32 g) combines with either 30 g of carbohydrate or 11 g of oil, they assumed that in rapeseed respiration 1 g molecule of oxygen would combine with (32 + 11)/2 = 20.5 g of dry matter. With these assumptions they calculated the safe storage periods in days shown in Fig.3.10. Although derived in a totally different way, these times do show remarkable agreement with those of Kreyger (1972) and Burrell et al. (1980). The real significance of this work, however, is that it provides functional relationships which could be used within a simulation of drying and storage to calculate dry matter loss, moisture increase and heat release under the variable conditions found in a seed bulk.

Recently Magan (1991) has also presented data on the respiration rates of rapeseed, cv. Libravo, determined at temperatures of 20, 25 and 30°C and nominal relative humidities of 70, 85, 90 and 95%. Although not reported in the paper, the moisture contents (Magan, Personal Communication) varied from 8.4 to 27.1% w.b. By using equation (3.43) to estimate the actual relative humidities consistent with Schmidt and Jacobsen's data and converting rates of oxygen consumption to the same units as used by Schmidt and Jacobsen, Magan's data were found to show remarkably good agreement with Schmidt and Jacobsen's and are also plotted in Fig.3.9. Unfortunately, Magan does not present values of carbon dioxide consumption and of the respiratory quotients, to compare with those of Schmidt and Jacobsen.

Muir et al. (1985) have investigated the use of carbon dioxide detection in a rapeseed bulk as an indicator of spoilage. They concluded that (a) active spoilage of stored cereal and the presence of insect pests can be detected in many farm granaries by measuring the concentration of $C0_2$ in the interseed air, (b) elevated $C0_2$ concentrations in granaries are nearly always an indication of active spoilage, (c) the best sampling point for measuring $C0_2$ concentration is in the spoilage pocket but when this is unknown the next best point is at the centre of the bin about 1 to 2 m below the grain surface, and (d) the required resolution of a $C0_2$

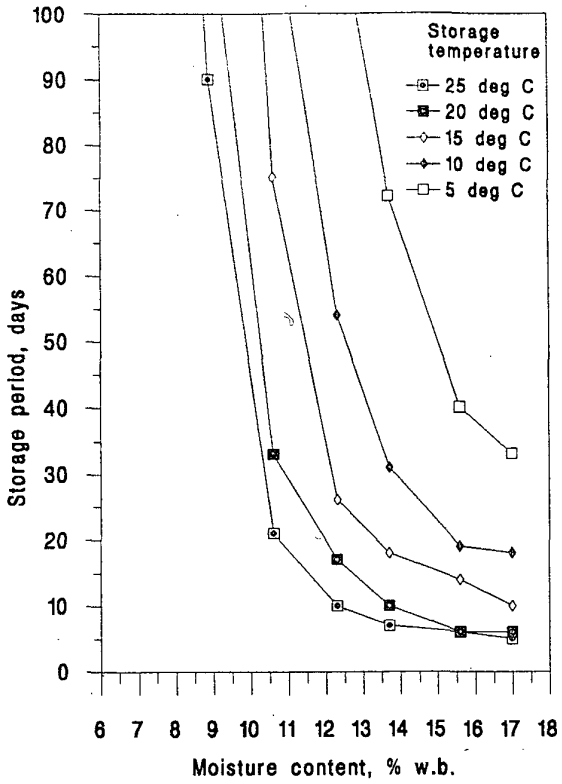

Fig.3.6 Effect of storage temperature and moisture content on the time to the appearance of visible mould (Burrell et al. 1980).

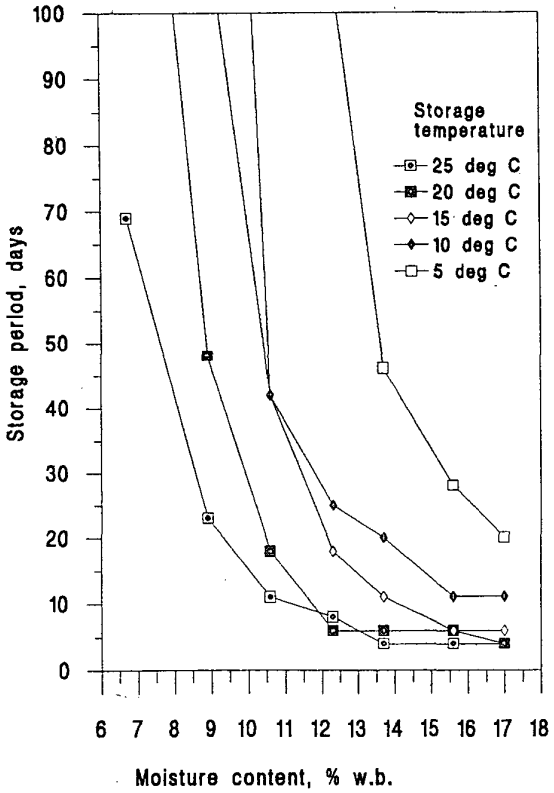

Fig.3.7 Effect of storage temperature and moisture content on the time to 'seed clumping' (Burrell et al. 1980).

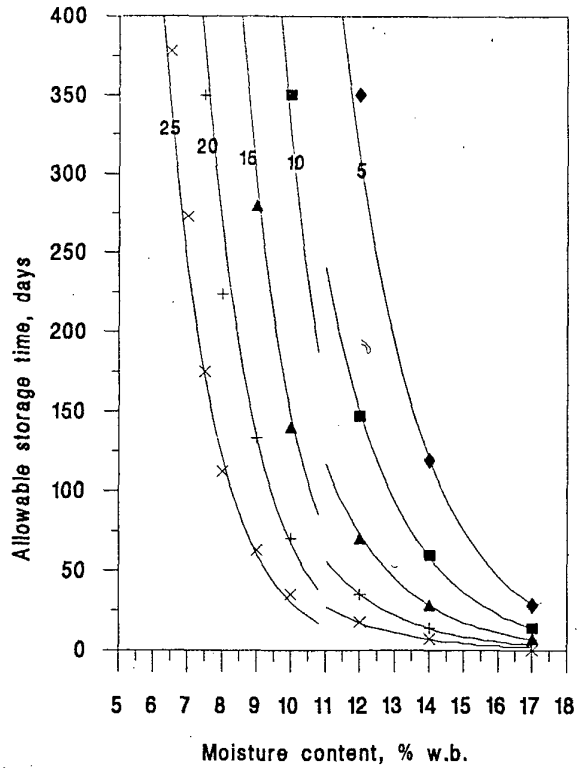

Fig.3.8 Allowable storage times given by Kreyger (1972), (Table 3.9) plotted as data points on curves generated by the equations (3.40) and (3.41) of Sinha and Muir (1986).

monitor is 0.01% $C0_2$ although a resolution of 0.1% may be adequate in many situations. As far as we are aware this detection technique is not widely used. Our guess is that it may not be any better, cheaper or more convenient than using temperature sensors and low volume ventilation to keep the seed cool (see Section 4.3).

Finally, we have seen that Burrell et al. (1980) concluded that first 'seed clumping' and then visible mould preceded germination loss. Nevertheless Burrell presented some germination data which are worth noting. They cover storage temperatures for 5 to 25°C and moisture contents from 6.7 to 17% w.b. for periods of 7, 21 and 35 weeks. These periods are too few for an analysis of 'probit' death rates of the individual conditions (Section 3.2.1.1) but the plots on linear axes (Fig.3.11) suggest that the germination decline conforms to the 'probit' hypothesis and that it might be possible to fit the 'probit' model to the data as a whole. The rapeseed used in this work had an initial germination between 98 and 100% and the decline occurred over a period of weeks. In contrast, Magan (1991) used seed with an initial germination of only 75% and storage period of only 7 to 28 days. The results were very variable and contained some inexplicably high values, e.g. 82 and 84%, but nevertheless showed generally a much more rapid decline. This again accords with the 'probit' hypothesis and it could be that the initial quality of the seed explains why Kreyger storage times based on germination are close to those of Burrell et al. (1980) based on appearance of visible mould.

It was suggested in Section 3.2.1. that rapeseed, which had been killed by excessive drying temperatures, was likely to deteriorate more quickly than seed of high viability. Sinha and Wallace (1977) refer to this likelihood but in their comparison of the long-term storage of barley and rapeseed *(Brassica napus* cv Zephyr), the rapeseed had a high initial germination and 'most seeds remained viable even when the fat acidity value was rapidly rising'. The keeping quality of the oil in heat damaged seed has not been investigated although circumstantial evidence suggests that it would be poor.

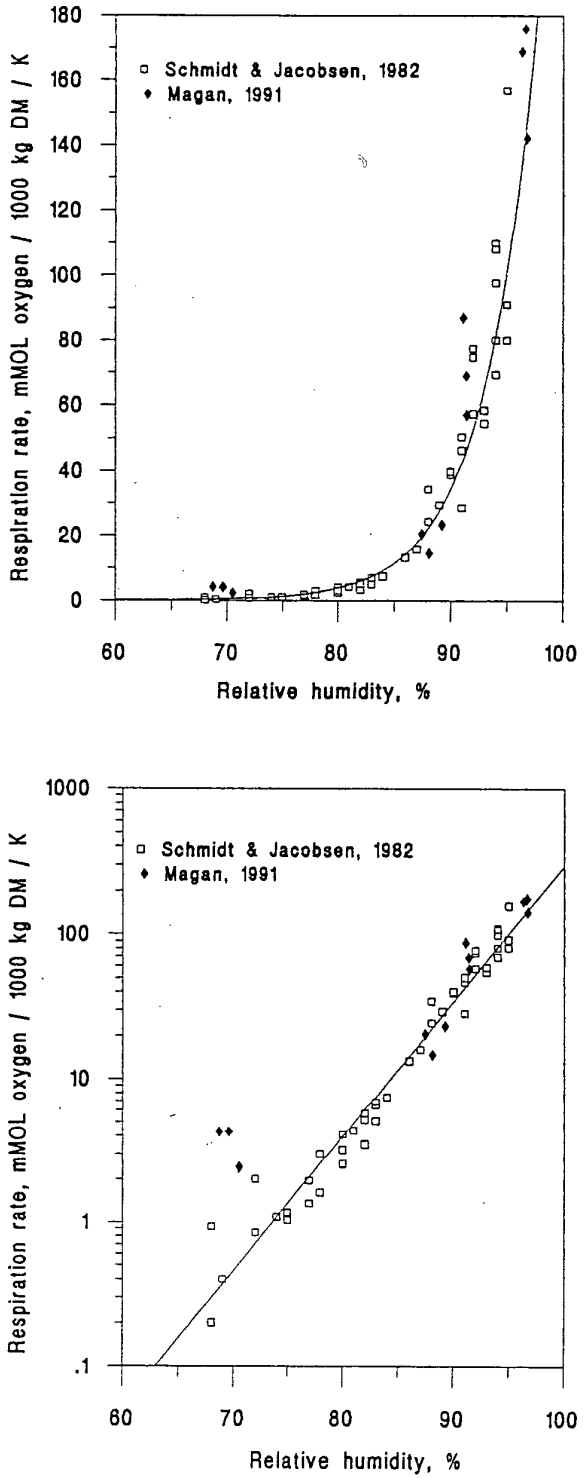

Fig.3.9 Effect of relative humidity on the respiration of rapeseed

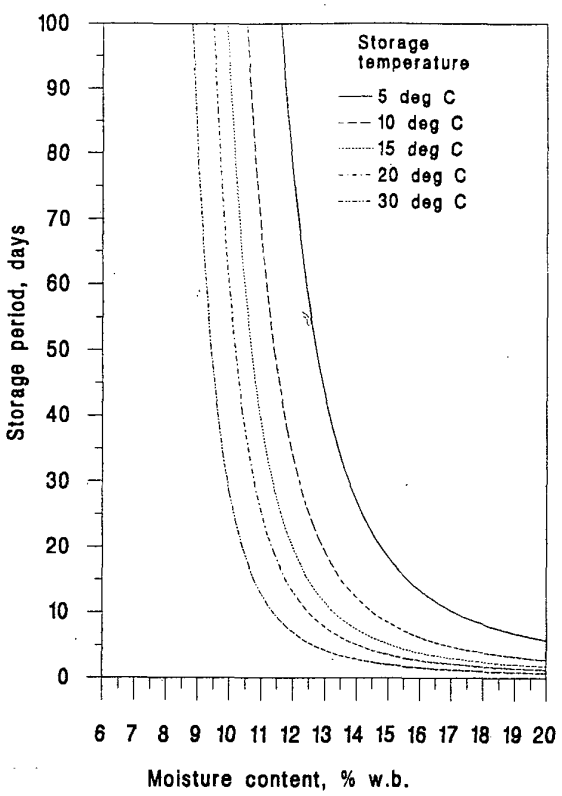

Fig.3.10 Effect of moisture content and storage temperature on the safe storage period computed by Schmidt and Jacobsen (1982) on the basis of 0.1% loss of dry matter.

The following conclusions may be drawn from this section.

- Allowable storage times proposed by Kreyger (1972) on the basis of germination studies were in agreement with those of Burrell et al. (1980) based on the development of visible mould. Burrell et al. also found 'seed clumping' to be an indication of significant spoilage and this occurred before the mould became visible. Kreyger's data have formed the basis of equations used in the calculation of a 'spoilage index' in computer-simulated drying and storage studies.

- Safe storage periods based upon a 0.1% dry matter loss, computed from measurements of respiration rate, were in surprisingly good agreement with those predicted by Kreyger (1972) and Burrell et al. (1980).

- Respiration rate studies are of particular importance because of their applicability to computer studies of drying and storage. They allow both local and overall losses of quality to be assessed and allow the moisture and heat produced to be included in the heat and mass transfer calculations.

- Damp seed of good quality is likely to mould before it loses germination, but more data is needed on the decline of dry seed in long term storage and of the interaction between initial germination (as affected by high temperature drying for example (Section 3.2.1.)) and increases in fat acidity and peroxide value.

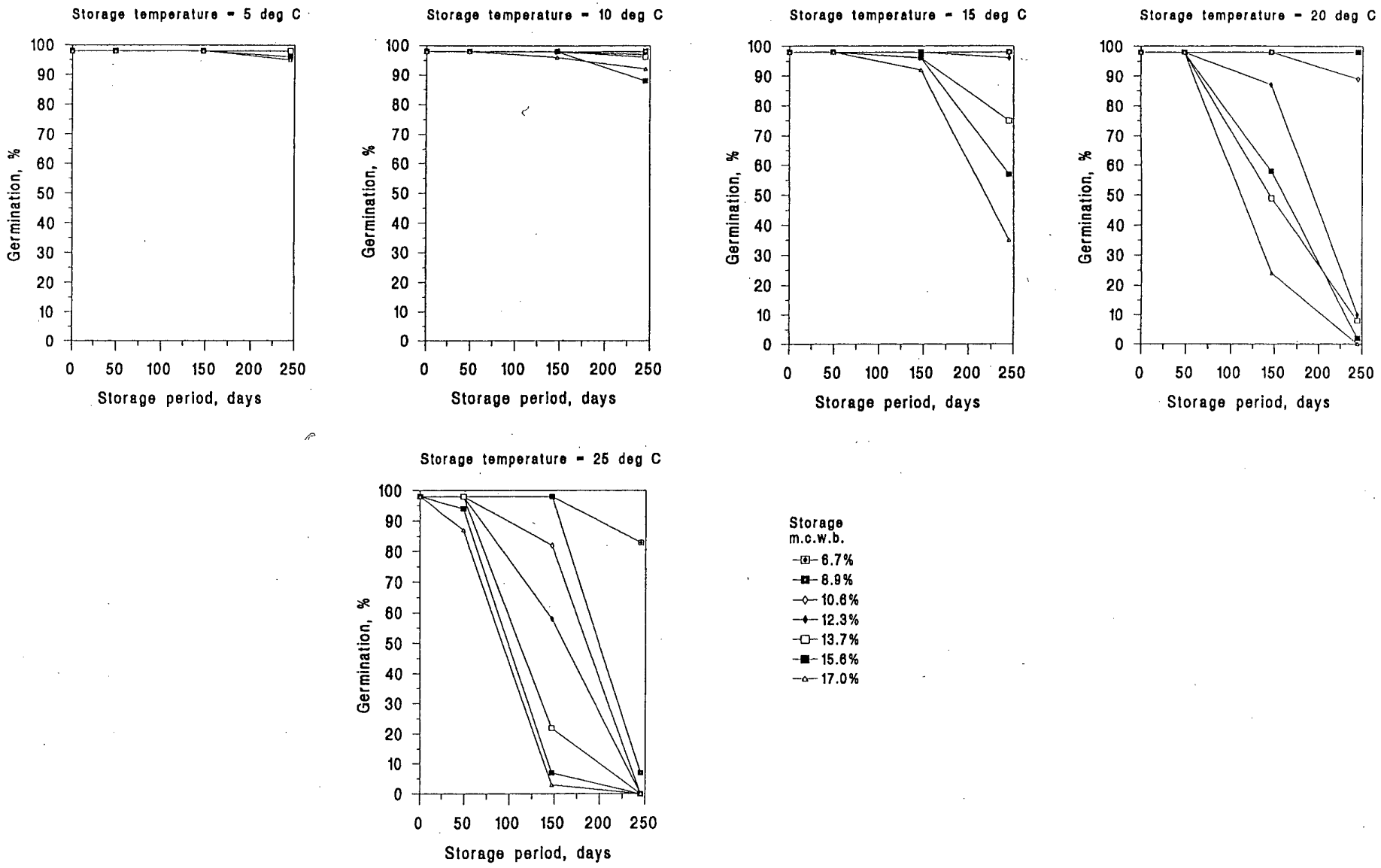

Fig.3.11 Interaction of storage time and storage temperature on the germination of rapeseed initially at 98 - 100% and at moisture contents from 6.7 to 17.0% (Data of Burrell et al. 1980).

4. Drying

4.1 Drying with heated air

4.1.1 Principles of drying with heated air

Heated air is used for drying crops to speed up the process of achieving safe storage moisture and to enable drying to proceed independently of the weather conditions. It is effective for three reasons. The capacity of the air to hold water in the form of water vapour increases nearly exponentially with temperature so that the quantity of air required to dry the crop and thus the size and cost of fans is reduced. Secondly, heat is transferred to the seed which increases the rate of moisture movement through the seed and thus the maximum rate at which it can dry if air is able to remove the moisture. Thirdly, heating the air reduces its relative humidity at inlet to the seed bed so that the first layers of seed with which it comes into contact are being dried towards a lower moisture. This increases the drying rate until the air becomes cooler and more humid as it passes into the bed.

If the air is heated, economical considerations demand that as high a temperature as possible be used to maximise the moisture evaporated by a given size of dryer. The limiting factor is that the seed will be damaged if its temperature becomes too high. The safe temperature to which the air can be heated before entering the grain bed and the effects of excessive temperature on rapeseed are discussed in Section 3.2.

The overall drying rate of the bed is determined by the rate of moisture removal in the exhaust air, given by the product of the air flow rate and the difference between exhaust and inlet absolute humidity. The humidity achieved by the air is determined by the condition of the seed near the point of air exhaust from the bed because, in general, the air will exhaust close to the equilibrium humidity corresponding to those seed conditions. There is little scope to increase this humidity, so the airflow which can be forced through the bed is the main determinant of the drying rate of the bed.

4.1.2 Special requirements for rapeseed

The small size of rapeseed relative to wheat has several implications for the design of heated air dryers. Because of the short distance across which the moisture within the seed has to move to reach the evaporation surface, the seed dries more rapidly than larger seeds. In addition a bed of small seeds has a greater surface area per unit volume of bed so that heat transfer from the air to the grain is more rapid. Both these points cause the air entering a bed of rapeseed to cool and become humid within a shorter depth than for wheat. Overdrying of seed at the inlet air side and re-wetting of the seed by condensation of moisture near the exhaust side of the bed are therefore possible.

A further consequence of small seed size is that the pressure needed to produce a given flow rate of air is higher than for, say, wheat because the air spaces between the seeds are smaller. Consequently, any given fan will produce a lower airflow when applied to a bed of rapeseed than through a wheat bed of the same depth. This reduction in airflow generally more than compensates for the inherently rapid drying rate of the seed itself so that overall the rate of moisture loss from a dryer drying rapeseed is less than that for wheat. It is a major limitation on the drying rate achievable with rapeseed in dryers which are deemed to be usable on a range of crops but basically have been designed for cereals. Also the air speed which can fluidise an

unconstrained bed of seed is lower than for wheat. In those designs of dryer in which the exhaust air emerges through an unconstrained seed surface, the airflow may have to be further reduced to avoid fluidisation of the seed and, in severe cases, elutriation of the seed from the bed. This limitation further reduces the overall drying rate achieved and eliminates the potentially faster drying of rapeseed compared to wheat. It also makes the cooling section of the dryer less effective.

In dryers in which the crop bed is constrained by perforated metal sheets, the perforations must be sufficiently small and suitably shaped to contain the seed but not be blocked by them, or airflow will be reduced. Therefore, slots rather than round holes are normally used. Perforated metal impervious to rapeseed itself offers more resistance to airflow than that designed to constrain only larger seeds.

The shallow angle of repose (Section 2.1.4), small size and spherical shape of rapeseed allow it to escape through gaps in equipment which retains other crops. This can give rise to seed running through the discharge device, normally situated at the base of a dryer, so that the grain flow is not so well controlled.

4.1.3 Types of heated air dryer and their characteristics

A good resumé of the various configurations of heated-air dryer is given by McLean (1989). Batch dryers load, dry, cool and discharge a batch of grain. In some dryers the batch is recirculated round the dryer to try to achieve more even drying treatment. In continuous-flow dryers the grain passes through a zone ventilated with heated air then through a zone using ambient air to remove a little more moisture and to cool the grain. The rate of flow of grain through the dryer, regulated by a variable-speed discharge mechanism at the outlet of the dryer determines the residence time in both the hot and cooling zones, and hence the moisture removal. Residence time must be longer if the seed is moister. It can be reduced if the air temperature can be raised, for reasons explained earlier, or if only small amounts of moisture need to be removed, but this reduces the residence time in the cooling zone and can result in seed being discharged to store at temperatures too warm for storage safe from pests. Cooling in store by a low flow of ambient air is then required (Section 4.1.4). The proportion of the drier used for cooling can, in some designs, be increased but this reduces the moisture removal that can be achieved by the dryer. In batch dryers, drying and cooling times can be independent so cooling can be prolonged but the time for drying is thereby reduced.

Where the grain is moved within either a recirculating batch or a continuous-flow dryer there are three basic flow configurations: cross-flow, counter-flow, and concurrent-flow, and one common hybrid, mixed-flow, are all suitable for drying rapeseed if well engineered.

McLean (1989), describes these types and their characteristic moisture and temperature profiles through the beds. Only those features relevant to rapeseed drying are discussed here.

In cross-flow, seed on the inlet side of the bed is subjected to air at the inlet temperature throughout the passage of seeds through the drying zone. Because of the high drying rate of rapeseed, this would cause a lower moisture relative to the equilibrium value than for wheat at this air inlet face in the bed. Consequently at the exhaust side, the air would be cooler and moister so the moisture gradient across the bed is likely to be significantly greater than for wheat. Several consequences are likely. Drier seed, being more brittle, is likely to be damaged during subsequent handling and can result in increased rancidity in the stored crop (Section 3.2.2). Even more so than with wheat, it is necessary to ensure that, when sampling the discharged

seed immediately after drying for moisture testing, a sufficient quantity is taken and is well mixed before being sub-sampled for testing. However, conveying to store would normally mix the drier and wetter seed sufficiently to encourage rapid equilibration. Seed which is overdried in a cross-flow or batch dryer would not necessarily be overheated, i.e. suffer thermal damage, but as the seed in these configurations of dryer approaches closely to the inlet hot air temperature, this temperature must be selected taking into account the thermal damage likely to be caused.

Counter-flow driers are not very common in the UK and would not seem to have problems particular to rapeseed but again, the seed comes into contact with the heated air so thermal damage is potentially a problem.

In mixed-flow and concurrent-flow dryers the seed is exposed only briefly to air at the inlet temperature so, in comparison with cross-flow types, there is potential for using hotter air without causing thermal damage. Concurrent-flow dryers make use of the initial rapid drying of the seed to ensure it remains below the inlet air temperature, and the rapid drying rate of rapeseed should enhance this effect relative to wheat. These dryers have not been commercially successful because of the long residence time in resting sections needed with large seeds such as maize, but such a long time may not be necessary with rapeseed. Shorter resting sections are, however, difficult to engineer.

Mixed-flow dryers are able to use air at higher temperature than cross-flow for a similar level of grain damage but the potential for higher temperatures is limited to about 5°C by the unevenness of temperature distribution at the ducts where air meets the grain. Hot spots in the plenum chamber can cause damage to grain and are difficult to locate. As the ducts are of inverted 'V' shape with open grain surfaces underneath there is no perforated metal to block with seed, which is a major advantage in that the dryer is easy to clean, but as air enters the exhaust ducts it can lift the seed and carry it out of the dryer. The airflow through a mixed-flow dryer operating on rapeseed may therefore have to be reduced to avoid this occurring. Most mixed-flow dryers use a duct spacing such that the bed depth is 0.15 to 0.2 m compared with 0.25 - 0.3 m depth for cross-flow and this results in a lower pressure drop across the seed bed. Together with the lower airflow referred to earlier, this results in a lower electrical power requirement for the fans in comparison with cross-flow dryers.

4.1.4 Fire risk in drying rapeseed

Fires in heated-air dryers are a hazard when drying any material, but more so with oilseeds because of the volatile fatty acids which can be released during drying (Lasseran, 1987) rather than because of oil evaporation. Nellist (1973) observed no losses of oil by evaporation from the seed during drying air temperatures of up to 71°C and noted that rapeseed oil does not contain very volatile component oils. High temperatures *per se* are not the cause of fires when drying rapeseed (Lasseran, 1987). The seed itself does not rise to a hazardous temperature until it reaches a very low moisture. This is only likely at a blockage, so cleaning the seed to remove any trash which could block the flow through the dryer is most important. Fires start in accumulations of dust and chaff in the dryer, so cleaning the dryer regularly is vital. Direct-fired dryers, where the products of combustion pass directly through the grain, are more likely to be involved in fires than indirect-fired dryers in which a heat-exchanger is used because hot particles passing into the grain bed are the normal cause of ignition. Spontaneous combustion is not the cause (Lasseran 1987). This was illustrated in experiments on rapeseed reported by Schmidt and Jacobsen (1982) in which particles of rust from the burner were found to have caused ignition. They recommended drying in two passes through

the dryer if initial moistures were above 20% w.b. so that the seed would move faster down the dryer and blockages would be less likely than in very slowly moving seed. No work has been found on where, and how, light fractions of crop accumulate in dryers and how such accumulations could be avoided. General practice for avoiding fires when drying sunflower seed, which apply equally to rapeseed, are given by Hellevang (1982) as

- constant vigilance
- cleaning of dryer at least daily
- avoidance of overdrying
- cleanliness of ingoing air

If a fire occurs rapid unloading of the dryer should be possible.

4.1.5 Performance on rapeseed in comparison with wheat

The rate of output of crop at a m.c. suitable for storage depends on the dryer design, the operating conditions and the crop parameters. Calculating the performance accurately is a very complex problem which can only be done by a computer simulation incorporating the parameters of both the crop and the drier. However, because the performance of dryers is normally quoted on wheat it seems reasonable to ask what fraction of the wheat output rate is generally achieved by dryers when drying rapeseed. If this fraction is substantially constant, the expected performance on rapeseed could be estimated from data on wheat drying.

There are four reasons why the output rate for rapeseed is different to that for wheat.

(a) the airflow through the crop bed will be lower, not only because the resistance to airflow will be higher for the given bed depth, but also because the airflow may have to be reduced deliberately to prevent elutriation of seed from unconstrained surfaces. The characteristics of the fan will determine how much reduction in air flow will be caused by the increase in resistance of the crop bed. If the reduction caused by the fan characteristic curve is insufficient, air may need to be bled in to the exhaust plenum from atmosphere to reduce the flow through the crop.

(b) the range of moisture over which the crop is dried may require more moisture to be evaporated per tonne of dried crop.

(c) the rate at which rapeseed can lose moisture, if the air is not near moisture equilibrium, is faster than for wheat.

(d) the drying air temperature appropriate to the crop in a particular design of dryer will differ between wheat and rapeseed.

As the comparison is evidently not straightforward, published performance test data have been reviewed so that some comparison can be drawn between the output rate of various dryers operating with wheat and rapeseed. The Prairie Agricultural Machinery Institute, PAMI, has published at least seven tests of dryers (PAMI, 1982a,b, 1983a,b, 1984a,b, 1985) operating on both wheat and rapeseed, results of which are summarised in Table 4.1.

Table 4.1
Results from PAMI test reports on dryers drying wheat and rapeseed

Report No.	Rated capacity, t/h		Drying air temperature, °C				Ratio of capacity on rapeseed to that on wheat
	Rapeseed	Wheat	Rapeseed		Wheat		
			Set	Actual	Set	Actual	
289	3.7	9.1	72	67	90	77	0.41
290	4.8	9.4	52	59	88	96	0.51
307	2.8	3.5	82	82	143	140	0.80
308	2.5	2.7	72	72	83	84	0.93
352	1.9	2.2	71	65	82	77	0.91
351	2.3	3.7	66	64	104	100	0.62
424	3.2	3.9	66	64	82	83	0.82

Though the inlet and outlet crop moistures and ambient conditions were not the same between tests, the test results were corrected to apply to a common set of crop and ambient conditions so that comparisons could be made. Details of the correction method, which makes assumptions that may not strictly be justifiable, are given by Wassermann et al. (1983). The tests were done by setting the drying air temperature dial to the manufacturers recommended value for that crop, then monitoring the actual temperature achieved, and its variation, during drying. The "rated capacity" was the calculated output rate for drying wheat from 19.5 to 13.5% wet basis and for rapeseed from 15.0 to 10.0% w.b. For each tonne at the final m.c. the dryers therefore had to remove 62.1 kg of water for wheat against 58.8 kg for rapeseed and would thus be expected to dry more rapeseed per hour were it not for factors (a), (c), and (d) above.

Two points are notable from the table. First, the fraction of the capacity on wheat which was achieved drying rapeseed was not consistent, ranging from 0.41 in Report 289 to 0.93 in Report 308. Inspection shows that this variation was not simply caused by a bigger difference between the drying air temperature used for wheat and rapeseed in the case of Report 289 for example. In fact the temperatures were very similar in the two cases. The main cause was most probably the difference in air flow between the crops which was not recorded in the test but evidently must have varied widely between the dryers tested. The dryer in report 289 achieved less than half of the drying rate, relative to wheat, of the dryers in reports 308, 352 and 424.

Second, the table reveals the wide discrepancy in air temperature recommended by the manufacturers for drying rapeseed as well as for wheat. The set value varied from 52 to 82°C. This range is too wide to be the result of a choice of values appropriate to the crop and dryer, and instead represents varying degrees of caution and uncertainty on the part of the manufacturer about the best temperature to use in each dryer. Also the ability of the dryers to achieve the set temperature varied, though this depends on the positioning of the test sensor. These points are relevant to Section 4.1.5 below.

Apart from a vast amount of experimentation, which is not a practical proposition, the only way to establish the appropriate air temperature setting for a particular dryer is to use simulation based on precise test data.

A recently revised standard (BSI, 1991) on test methods for grain dryers sets out appropriate techniques for measuring dryer output rate on wheat, and for correcting results to a set of standard conditions using simulation directly or a formula based on results of simulation. Calculation of safe temperatures for operation is becoming possible using such a simulation, checked against test data, to calculate the loss in quality experienced by a crop during the drying process. A model for seed viability by Nellist (1981) and for bread baking quality by Bruce (1991) are examples of the quality loss models which can be applied once the grain temperature and moisture histories in the dryer have been calculated by simulation.

Besides making possible fair comparisons between dryers, such a simulation is a powerful tool for improving the design of dryers (Miller and Whitfield, 1984) and for investigating methods of improving the control of output m.c. in unsteady conditions. (Whitfield, 1988).

4.1.6 Safe drying air temperatures

Apart from the question of which drying air temperature to select to give the highest possible drying rate without unacceptable loss of crop quality, there is also the more mundane but crucial point of how well the dryer can achieve the set value, which is determined by such factors as how accurate and well located the thermostat is, how much fluctuation about the mean temperature the burners cause and what temperature gradients are present across the hot air plenum as the air enters the grain.

Very few data have been found on the effect on rapeseed quality of drying in commercial-scale dryers, as opposed to under laboratory conditions. This is partly due to the expense of full-scale work and the fact that the results of such work can be difficult to interpret because of experimental problems. Also such investigation on particular dryers may be commercially sensitive. The PAMI test reports simply record the mean drying air temperature achieved, the output rate of grain, and the moisture contents of input and output grain. They do not record the quality of the input or output crop, other than to note if a "grade loss" occurred, i.e. if the dried grain quality fell below one of the Canadian Grain Commission quality standards because of drying. The value of full-scale tests is diminished if insufficient data is recorded to check the results of a simulation model. Such models can be used to carry out further simulation "experiments" and extend the usefulness of the test.

Schmidt and Jacobsen (1982) used a small continuous-flow dryer of the mixed-flow type operating at steady-state conditions. They dried rapeseed at air temperatures between 62 and 123°C, from moistures between 12.3 to 22.1% w.b. and, in four of the eight tests, they pre-heated the damp seed with air at 148°C in an attempt to increase the drying rate of the dryer. Output moistures were between 7.2 and 12.9% w.b. Samples of output grain were analysed for oil content, cracked seeds, germination, free fatty acid (FFA) content, peroxide value, anisidine value, phosphorous content, crude protein and dye binding capacity. Measurements were also made of the moisture and temperature of the exhaust air along the length of the drying column, and of the moisture and temperature of the seed at each of 10 points in the bed. Sufficient information is given to enable the tests to be simulated. This would be a valuable and highly efficient way of validating a simulation model of this process and of generalising the test results to other drying conditions. Even the standard deviations of most of the measurements are given which would be valuable if a comparison between measured and simulated results were to be made. Unfortunately such a simulation exercise is beyond the scope of this review.

Schmidt and Jacobsen found that they had to reduce the airflow by 60-70% compared with operation on wheat and barley to avoid elutriation of seed, so a proportionate fall in drying capacity was, as expected, observed. Pre-heating of the seed increased the capacity but by how much is unclear because each test used different conditions. Again simulation would be the best means to determine the effectiveness of the technique. Little lateral dispersion was found, so that the seed must have descended the column in streams, some passing a series of inlet ducts and becoming dryer than the mean, while other streams remained damp because they passed only exhaust ducts. So the range of moisture between the dryer and wetter streams of seed at the bottom of the drying section ranged from 6 percentage points of moisture in one case to 12 in another. Seed either drier or wetter than the target m.c. of 7 - 10% w.b. was more susceptible to mechanical damage. Germination was reduced by a mean of 64% in six tests with drying air temperatures of 108 to 122°C.

A significant reduction in FFA was noted as a result of drying whereas the peroxide value was unaffected. FFA increased during subsequent storage at a rate which increased with storage temperature though no details of the storage conditions are given.

Rapeseed is noted by Burghart (1988) as being more resistant to thermal damage than other common oilseeds, but elsewhere (Burghart, 1989) gives maximum temperatures without effect on oil quality as 85°C for rapeseed and 105°C for sunflower. The release of sulphur from thioglucosides in high glucosinolate varieties of rapeseed is also said to be a problem if the seeds become too hot. He recommends an air temperature below 75°C for rapeseed but this is not specific to any type of dryer and is not backed up by quoted experimental work.

Overall, there is little experimental work of good quality on drying of rapeseed in full-scale dryers and no analysis using simulation, without which the results of such tests as these are difficult to interpret.

Because dryers are designed to cope with a range of crops, the operating conditions required for rapeseed may be towards the extremes of the dryers' capability. The low airflow, the moderately low air temperatures and the high ambient temperatures likely at the time of rapeseed harvest all suggest that it may be difficult to set up the burner to combust efficiently and free of smoke, and to control it to achieve the set drying temperature. Airflow can be further reduced if the resistance to airflow of any seed-retaining mesh in the dryer increases because of dust adhering to its oil surface. There is anecdotal evidence to support these suggestions.

4.1.7 Control of moisture content

Moisture of crop entering a dryer will vary depending on its source and time of harvest. After drying, the crop should, ideally, all be discharged at the m.c. required for safe storage or sale. Thus the water to be removed from each unit of crop may vary, and so the dryer must be adjusted to achieve this. Normally the residence time of the crop in the heated air is adjusted by altering the throughput in the case of continuous-flow dryers, or the drying time in batch dryers, but the drying air temperature may also be adjusted. The advantages of, and problems in achieving, good control are the same for rapeseed as for wheat or barley. Good control can reduce overdrying leaving a greater mass of more uniform product for sale, increase the throughput of the dryer, and save on fuel and supervision cost. The improved uniformity of m.c. may prevent localised problems caused by wet patches even if the overall m.c. is satisfactory. The problems in achieving good control are a) how to sense the crop m.c. accurately and b) what actions to take in response.

Sensing the output and input m.c. of the crop is normally done by manually sampling the grain and measuring its moisture off-line. Care needs to be taken that a representative sample has been obtained, and the wide range of m.c. with rapeseed between the wetter and drier streams of grain make this even more important with rapeseed than with wheat. Such sampling and direct measurement of m.c. is not easy to automate though one device on the market, manufactured by Fyfe Electronics, claims to do so. A system recently marketed by Carier B.M.H. Ltd. uses an in-line sensor, the calibration of which can be adjusted to match occasional off-line measurements made by the operator. A more common method of sensing output crop mc. depends on the fact that hot air passing through damp crop cools by an amount depending on the moisture evaporated from the crop. Thus by sensing the temperature of the air emerging from the crop near the bottom of the drying zone or, for a batch dryer, near the end of the drying time, the moisture of the crop can be inferred. However, the relationship between crop m.c. and exhaust temperature is complex. The temperature corresponding to the desired m.c. must be found from trials and is affected by the inlet air temperature, the inlet crop temperature, the air flow rate and how much moisture has been removed, if this is small. The exhaust temperature method is thus not easy to use. With rapeseed the principle of the method still applies but the practice has not been studied in the literature.

The action of a controller can be improved by using the inlet crop m.c. to anticipate and correct for deviations caused by changes in ingoing m.c. Exhaust air temperature sensing cannot be used in this way because the inlet crop is normally too damp and the exhaust temperature is not responsive to the m.c. Direct measurement is the only choice, though automation of sampling wet crop, which does not flow easily, is difficult.

For a given moisture content reduction, the discharge rate achieved on rapeseed is lower and the residence time is longer than for wheat, as indicated in Table 4.1. So the delay between an adjustment to the discharge rate and its effect on the output m.c. will also be longer. The control actions taken for a given moisture error at the output must therefore be more gradual otherwise an unstable response will occur as a result of which the output moisture swings around the target and does not stabilise. Thus the control of a continuous dryer on rapeseed is more difficult than on wheat. No references have been found specifically dealing with the control of rapeseed drying but from the underlying principles and experience with cereals, the difficulties of accurate control are known to be considerable.

4.2 Drying with air at near-ambient temperatures

Rapeseed can be dried in conventional floor- and radially-ventilated bins and in on-the-floor ventilated duct systems, provided the perforated ducts or screens which separate air from seed, do so without significant increase in resistance to air flow. (Some round hole perforations can be completely blocked by seeds acting like poppet-valves). The important physical requirements in designing or operating a system are to size the fan and any necessary air conditioning equipment, to determine how to vary bed depth and to adjust operational parameters in relation to seed moisture content and the weather conditions.

There have been virtually no scientific studies of near-ambient drying under UK conditions and existing advice is based very much upon rules-of-thumb. McLean (1989) recommends a maximum depth of 1.2 m and airflows of 0.1 to 0.15 m/s for drying seed of 14% m.c. or less. For seed of higher moistures he recommends even shallower layers but cautions against reducing layer depth to less than twice the duct spacing in on-floor systems. McLean's airflow rates are equivalent to 130 to 188 litres/(s tonne) of crop.

In an earlier report, Oldfield et al. (1979) had suggested airflows of from 17 to 167 litres/(s tonne) depending upon moisture to be removed when drying to 8% (Table 4.2).

These values were computed (Nellist and Dumont, 1978) pro rata from the airflow rate recommended (MAFF 1982) for drying wheat from 21 to 15% (76 kg water removed per dried tonne). Nellist and Dumont (1978) went on to calculate, from the pressure characteristics of spring and winter rape (Matthies and Petersen, 1974), the combinations of bed depth and fan pressure required at each moisture level to obtain these airflows.

Table 4.2
Required airflows for near-ambient drying of rapeseed.
Adapted from Oldfield et al. (1979)

Initial moisture content, % w.b.	Airflow l/(s tonne)	Moisture removed per dried tonne, kg
10	17	22
12	36	45
14	55	70
16	76	95
18	97	122
20	119	150
22	143	179
14	167	211

These data were presented as charts, which were also reproduced by Oldfield et al. (1979), who extended them to the case of radial bin drying. Table 4.3 illustrates these relationships for fan pressures of 50 and 100 mm w.g. compared with the values calculated for drying barley to 15%.

As already stated these values were computed on the basis of rule-of-thumb and paid no regard to the drying properties of the crop or the vagaries of the weather, other than to use measured pressure resistance values and to make a reasonable assumption about specific air consumption.

In Canada, Sharma and Muir (1974) developed a computer model of rapeseed drying based on the near-equilibrium model of Bloome and Shove (1971) and showed that predicted results were close to those obtained in a laboratory drying experiment. Muir and Sinha (1986) using the near-equilibrium model of Metzger and Muir (1983) used computer simulation to determine airflow rates necessary to dry rapeseed by continuous ventilation under Canadian conditions. Drying from three initial moisture contents, 11, 13 and 15% w.b. and at three harvest dates, 15 Aug, 1 and 15 Sept, was simulated for each of 15 years' weather data from four locations on the Prairies. Spoilage was computed by the equations fitted to the data of Kreyger (1972). Predicted results were compared also with experimental data from 26 tons of the cultivar Regent freshly harvested at 14.4%. Compared with the experimental results, the model predicted more reabsorption during periods of high humidity in late October, November, and December, than was measured. Otherwise agreement was good. No significant spoilage was predicted and no significant spoilage occurred.

Table 4.3

Depths of drying bed giving airflows equivalent to those of Table 4.2 at two levels of fan pressure and compared with similar data for barley dried to 15% moisture content

Pressure drop through seed, mm w.g. (Pa)	Initial moisture content, % w.b.	Depth, m		
		Rapeseed		
		Spring	Winter	Winter barley
50 (498)	10	2.1	3.3	
	12	1.5	2.2	
	16	0.98	1.5	5.0
	20	0.76	1.1	2.0
	25	0.61	0.88	1.1
100 (996)	10	2.9	4.5	
	12	2.0	3.0	
	16	1.3	2.0	6.8
	20	1.1	1.5	2.7
	25	0.85	1.2	1.8

By repeated running of the program the airflows necessary to achieve drying to 10% after 15 - 20 days without spoilage were found and expressed in terms of the medium year, i.e. the year with median drying time. By this definition the theoretical minimum rates of airflow were found to vary from 11 to 25 l/(s m^3), ($\approx$17 to 39 l/(s tonne) increasing with initial moisture content and harvest date. Drying times to 8% w.b. were also computed and increased energy consumption by 30-60% compared with drying to 10% w.b.. In further work Muir et al. (1989) monitored the physical and biological changes in two bins filled to a depth of 3.5 m with rapeseed at 13% m.c.w.b. One bin was ventilated from the time of filling, 15 September, 1987, to 10 December of the same year with air at 5.0 l/(s m^3), (= 7.8 l/(s t)). The other bin was not ventilated and monitoring in both bins continued until 24 June, 1988. Cooling and drying during the ventilated period was simulated and the deterioration model was used to predict quality change in both bins. The drying model was found to predict adequately the temperature and moisture changes in the ventilated seed and the deterioration under predicted quality changes in both. Sharp increases in the deterioration index were preceded by increases in measured CO_2 in both ventilated and non-ventilated bins. It was found also, that a deterioration index greater than 1.0 may not necessarily predict spoilage but that a rapid increase in the index seemed to be a better indication of spoilage.

Although none of these studies have explored adequately the relationships between fan pressure, bed depth and initial moisture content or the effect of weather, they have been put to practical use by Huminicki et al. (1986) in a microcomputer-based design package intended for use by advisory engineers. The program provides information on recommended airflow rates, fan selection and ventilation system performance for several crops including rapeseed. A simplified version of the near-equilibrium model (Muir and Sinha, 1986) is an integral part of the program.

The authors (Huminicki et al. 1986) report that the program has been well received but list several areas in which further work is required. Those relevant to this review include the need to validate the simulation more thoroughly, particularly for strategies involving heaters and controls and the need to increase the speed of execution. Concern was expressed also about the accuracy of spoilage prediction and further development of spoilage models was recommended.

In the UK, a simulation model specifically for rapeseed does not exist although the program STOREDRY (Sharp, 1982; Sharp et al., 1982; Brook, 1987; Hodges et al. 1988) used at Silsoe Research Institute to study the near-ambient drying of cereals (e.g. Nellist, 1988; Nellist and Bartlett, 1988; Ryniecki and Nellist, 1991 a,b) could be adapted with very little difficulty.

4.3 Cooling

After the initial drying to bring the seed to equilibrium relative humidities at which fungi will not grow, the next priority is to reduce the seed temperature both to further stifle fungal growth, but more importantly prevent the growth of insects and mites. Since there is negligible moisture transfer, dry seed can be cooled with far less air than is needed for drying. Thus 'low volume ventilation' rates are only about one-twentieth of those required for drying. Nevertheless, the ventilation periods may span many months and it is important to ensure that the cooling is efficient. For safety the seed needs to be cooled to less than 5°C (Armitage, 1980) and in the UK such temperatures can be achieved by judicious use of ambient air. Hunter (1986) points out that for a given airflow there will be an optimum fraction of each day at which the ventilation fan should be switched on. If this aeration time fraction (a.t.f.) is too low then the cooling front will take a long time to pass through the bed; conversely if the fraction is too high then the average aeration temperature will be so high as not to cool the seed. Similarly for a blowing system there will be, for a given aeration time fraction, an optimum airflow which maximises the rate of cooling. This is because too low a flow would mean that the cooling front would take a long time to pass through the bulk, and, too high a flow would involve an excessive temperature rise through the fan.

It follows that there can be found a simultaneous optimum airflow and a.t.f. and that these will vary with time as the seed bulk cools. In the case of a sucking system, there will be an optimum aeration time fraction but there will be no optimum airflow because the temperature rise due to the fan occurs after the air has passed through the seed. Hunter (1986) went on to develop an analytical basis for determining these optimum values in relation to the external weather and the progress of cooling within the crop. Both blowing and suction aeration systems are analysed and the examples are based on the time-proportioning controller developed by the CSIRO (Elder, 1972) with Australian wheat as the specimen crop. The work was applied neither to UK conditions nor to rapeseed, but were such a project to be undertaken, the benefit in terms of better storage conditions and less energy used to achieve them could be considerable.

In the UK, work of a different kind (Armitage, 1980) has confirmed the efficacy of cooling by aeration for limiting mite infestation. Two experiments were carried out with rapeseed at 8% and 9% moisture content stored over 20 and 9 months respectively in bins of 10 - 12 tonne capacity. Unaerated bins were compared with bins aerated at about 4.7 l/(s t) under the control of a thermostat which was adjusted weekly to restrict ventilation to those periods when the air temperature was below that of the average seed temperature. Armitage states that the main difference between the temperature of aerated and unaerated bins was that the former spent a considerably longer time below 5°C between each winter and spring. Aeration was effective at controlling mite growth at both moisture levels but slightly more effective at the lower (8%) level.

Apart from the mites there were no quality changes of economic importance in any of the bins. Energy consumptions were of the order of 20 kWh/tonne stored i.e. about £1 per tonne at current electricity prices. Similar large-scale experimental studies in Canada (Mills et al. 1984, Sinha et al. 1981) support Armitage's conclusions.

5. Conclusions

The overall picture which emerges from this, Part I of the review, is that, for such an economically important crop, the available information on rapeseed is not adequate.

Data on the fundamental properties of rapeseed is variable; some aspects are well covered although much of the work was done on varieties now outdated, while other areas are poorly, or not, covered. To highlight those two areas in which the necessary information falls short of the minimum required for good design and operation of rapeseed drying and storage systems, we have categorised the properties as adequate, not adequate and not available.

The technology for improving rapeseed drying and storage practice is also lacking. In some problem areas the problems are common with those of cereals and a common research approach could be the most efficient method of progress, whereas in other areas the route is clear from progress with cereals and simply requires implementation in the context of rapeseed. Only in the interacting effect of loss of viability and oil quality was the identified problem unique to rapeseed.

5.1. Basic information on the properties of rapeseed

5.1.1. Adequate

Data of adequate quality and covering a range of conditions suitable for drying and storage were available for the following parameters:

Relationship (data and describing equations) between pressure across and airflow through rapeseed in bulk, provided that airflow is parallel;

Relationship (data and describing equations) between rapeseed moisture content and air relative humidity at equilibrium;

Solid density, bulk density and porosity;

Size, shape, mass per seed;

Specific heat capacity of rapeseed;

Thermal conductivity;

Thermal diffusivity;

Net heat of desorption of water.

5.1.2. Inadequate

For the following parameters information was inadequate.

Although some good quality data on the drying rate of single layers of seed exist, further analysis is needed to express them in suitable form for general use in heated-air drying calculations.

The available data on the effect of seed temperature on its rate of quality deterioration during heated-air drying is poor. The interaction with moisture content, which makes seed more susceptible to thermal damage but also, by evaporative cooling, helps to keep the seed cool, has not been adequately explored. Without good data, the effects of drying treatments on quality cannot be evaluated and equipment cannot be designed for or operated for optimal performance.

Respiration rates of seed in bulk are vital to enable overall and local losses of quality to be assessed, through the technique of computer simulation, in drying and storage situations. The rate of mould growth and respiration at temperatures and moistures pertaining to near-ambient drying has not been adequately explored.

Some theoretical work has been done on the resistance to airflow for ventilation patterns other than those which give parallel airflow. This work needs to be validated and made known for general use.

5.1.3. Not available

For the following parameters no data were found in the literature.

Heat transfer coefficient. No data was found on the rate of exchange of heat between seed and the air with which it is ventilated, from which values of the heat transfer coefficient can be derived. The heat transfer coefficient is necessary for calculation of seed temperature and, thereby, of any resulting seed quality loss during heated air drying.

Resistance to airflow of beds of seed several metres deep. The need to design and operate cooling equipment for deep beds of seed over many months, during which the seed may settle, requires data on the resistance to airflow of such beds. No such measurements on deep beds were found. No information was found on the increase in resistance when deterioration of the seed has caused it to start "caking" or "clumping".

If the seed viability is reduced during drying with heated air, the quality of the oil in seed stored for long periods will deteriorate. No information on the rate of deterioration in relation to storage conditions was found.

Repose angle. No data was available on the angle of repose of moist bulk seed, of flowing seed, or of seed stored at bed depths likely to cause compaction.

5.2 Information on practice of drying and storage

Whilst this review has been concerned with scientific literature, there was a noticeable lack of information on current practices and problems within the industry. Such information is necessary for assessing priority areas for further research.

The available information is again less adequate than for wheat. Despite the advantages in throughput and efficiency to be gained by running a dryer at as high an air temperature as possible, the limiting temperature for drying of rapeseed to preserve viability in various types of dryer has not been investigated adequately . Some data are available but they were obtained using a laboratory-scale mixed-flow dryer and need further analysis and confirmation. Because of the limited evidence no recommendation can be made as to whether the MAFF recommended safe temperature for preserving viability is the most appropriate. There is no MAFF recommended safe temperature for oil quality.

In those types of heated air dryer having open seed surfaces it is necessary to reduce airflow to avoid problems of seed elutriation. This reduces the throughput of the dryer. No studies were found on how this reduction could be minimised so that the performance of dryers on rapeseed could be maximised, or on how the accuracy of temperature control, important for avoiding loss of seed quality, could be improved in low airflow, low temperature rise conditions.

To investigate the design and operation of both heated-air and near-ambient dryers on rapeseed, validated computer simulation models are needed so that initial studies on design and operation can be carried out rapidly, and the move made to full-scale equipment only when the basic design parameters are correct. Such simulations have been developed in the UK for wheat and for wheat and rapeseed in Canadian conditions. Their conversion for rapeseed drying in UK conditions is straightforward.

Using near-ambient dryers on rapeseed is as complex as on wheat. Basic design layout of such dryers is understood but how to maximise the drying capacity of a given installation is not. The best control strategy for the operation of fan and any air conditioner is likely to differ from that for wheat because, although the weather is likely to be more favourable, rapeseed heats rapidly and has a tendency to form a crust which restricts airflow. The principles of automatic control of near-ambient dryers are not at all well defined, for rapeseed or other crops.

Existing theory on cooling optimisation could be applied to rapeseed, using models of drying and storage converted for rapeseed.

In heated-air, continuous-flow dryers the principles of moisture control are now better understood but new equipment coming onto the market has yet to prove itself in commercial practice.

Risk of fires in dryers on oilseed may be minimised by precautionary measures which are well-known but perhaps not well enough practised. Improved design of dryers is needed to avoid the accumulation of chaff and dust.

The performance of electrical moisture meters on rapeseed is very variable. In Canadian tests, meters using the capacitance method were much more satisfactory than resistance meters. No comparable work under UK conditions or with current varieties of rapeseed has been published.

Although there have not been any systematic studies of differences in the drying and storage behaviour between *B.Napus* and *B.Campestris* species, available data do not suggest that such differences are large or that they cannot be explained by seed size and oil content. Differences in drying and storage behaviour between standard and "double low" varieties cannot be discerned with any confidence, given the fragmented evidence available.

6. Recommendations

Based on the conclusions of this review the following recommendations are made.

1. The deterioration of rapeseed by moulding, in relation to conditions of near ambient drying and of storage, should be quantified and published in a form which designers and operators can use easily.

2. Cooling of deep beds should be investigated to determine the combination of equipment and the strategy which will cool most effectively with ambient air, given that rapeseed has a high resistance to airflow and that the cooling air becomes heated by its passage through a fan proportional to the pressure generated. Optimum cooling strategies should be studied, using simulation models, to improve the effectiveness and efficiency of cooling rapeseed.

3. A means of selecting the maximum drying load of a given near-ambient installation on rapeseed should be devised and publicised.

4. Safe drying temperatures in heated-air drying:- Work should be done to determine the relationship between loss of rapeseed quality (viability and oil quality), and seed temperature and seed moisture. The results of this work should then be used to determine the safe temperatures at which heated-air dryers of various types can be operated. The most cost effective means of applying the results would be by a progression of simulation, small-scale and full-scale tests.

5. Existing data on drying rates of rapeseed should be analysed and made available. The heat transfer coefficient for rapeseed should be investigated experimentally to validate predictions made from experiments on other particles.

6. Loss of viability of rapeseed in long term storage and changes in oil quality resulting from low seed viability should be investigated and quantified.

7. Performance of moisture meters in UK farm and commercial use on rapeseed should be investigated.

8. Simulation models of near-ambient and heated-air drying developed for wheat, should be converted to simulate rapeseed drying. They would be valuable in the above tasks (1 - 4) and the conversion would be straightforward. Versions for personal computers should be developed and made available at minimal cost to growers.

9. With the reservation that most store operators would be reluctant to admit to having problems, a survey of current drying and storage practices and problems would help to identify priorities for further research.

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Appendix. Sorption data.

T = temperature, deg C
RH = rel. humidity, %
DB = m.c.w.b., %
WB = m.c.d.b., %

Pixton & Warburton, 1977

Gulle - Adsorption

T	RH	WB	DB
5.0	30.0	4.2	4.4
5.0	40.0	5.0	5.3
5.0	50.0	5.8	6.2
5.0	60.0	6.8	7.3
5.0	70.0	8.1	8.8
5.0	80.0	10.6	11.9
5.0	90.0	14.7	17.2
15.0	30.0	4.1	4.3
15.0	40.0	4.8	5.0
15.0	50.0	5.6	5.9
15.0	60.0	6.5	7.0
15.0	70.0	7.9	8.6
15.0	80.0	10.3	11.5
15.0	90.0	14.3	16.7
25.0	30.0	3.8	4.0
25.0	40.0	4.6	4.8
25.0	50.0	5.4	5.7
25.0	60.0	6.3	6.7
25.0	70.0	7.7	8.3
25.0	80.0	10.2	11.4
25.0	90.0	14.1	16.4
35.0	40.0	4.4	4.6
35.0	50.0	5.2	5.5
35.0	60.0	6.2	6.6
35.0	70.0	7.5	8.1
35.0	80.0	10.1	11.2
35.0	90.0	14.1	16.4

Gulle - Desorption

T	RH	WB	DB
5.0	20.0	3.7	3.8
5.0	30.0	4.5	4.7
5.0	40.0	5.3	5.6
5.0	50.0	6.1	6.5
5.0	60.0	6.9	7.4
5.0	70.0	8.4	9.2
5.0	80.0	10.9	12.2
5.0	90.0	15.2	17.9
15.0	20.0	3.4	3.5
15.0	30.0	4.2	4.4
15.0	40.0	5.0	5.3
15.0	50.0	5.8	6.2
15.0	60.0	6.8	7.3
15.0	70.0	8.1	8.8
15.0	80.0	10.6	11.9
15.0	90.0	14.7	17.2
25.0	20.0	3.3	3.4
25.0	30.0	4.1	4.3
25.0	40.0	4.8	5.0
25.0	50.0	5.6	5.9
25.0	60.0	6.5	7.0
25.0	70.0	7.9	8.6
25.0	80.0	10.3	11.5
25.0	90.0	14.3	16.7
35.0	20.0	3.1	3.2
35.0	30.0	3.8	4.0
35.0	40.0	4.6	4.8
35.0	50.0	5.4	5.7
35.0	60.0	6.3	6.7
35.0	70.0	7.7	8.3
35.0	80.0	10.2	11.4
35.0	90.0	14.1	16.4

Hektor - Adsorption

T	RH	WB	DB
5.0	40.0	4.7	4.9
5.0	50.0	5.5	5.8
5.0	60.0	6.6	7.1
5.0	70.0	8.0	8.7
5.0	80.0	10.2	11.4
5.0	90.0	15.0	17.6
15.0	40.0	4.5	4.7
15.0	50.0	5.3	5.6
15.0	60.0	6.4	6.8
15.0	70.0	7.7	8.3
15.0	80.0	9.9	11.0
15.0	90.0	14.5	17.0
25.0	40.0	4.4	4.6
25.0	50.0	5.2	5.5
25.0	60.0	6.2	6.6
25.0	70.0	7.5	8.1
25.0	80.0	9.6	10.6
25.0	90.0	14.2	16.6
35.0	40.0	4.2	4.4
35.0	50.0	5.0	5.3
35.0	60.0	6.0	6.4
35.0	70.0	7.3	7.9
35.0	80.0	9.5	10.5
35.0	90.0	13.8	16.0

Hektor - Desorption

T	RH	WB	DB
5.0	20.0	3.6	3.7
5.0	30.0	4.4	4.6
5.0	40.0	5.3	5.6
5.0	50.0	6.3	6.7
5.0	60.0	7.3	7.9
5.0	70.0	8.6	9.4
5.0	80.0	10.5	11.7
5.0	90.0	15.0	17.6
15.0	30.0	4.2	4.4
15.0	40.0	5.1	5.4
15.0	50.0	6.1	6.5
15.0	60.0	7.1	7.6
15.0	70.0	8.4	9.2
15.0	80.0	10.3	11.5
15.0	90.0	14.5	17.0
25.0	30.0	3.8	4.0
25.0	40.0	4.7	4.9
25.0	50.0	5.7	6.0
25.0	60.0	6.8	7.3
25.0	70.0	8.2	8.9
25.0	80.0	10.1	11.2
25.0	90.0	14.2	16.6
35.0	40.0	4.3	4.5
35.0	50.0	5.4	5.7
35.0	60.0	6.6	7.1
35.0	70.0	7.9	8.6
35.0	80.0	9.9	11.0
35.0	90.0	14.0	16.3

Tower - Adsorption

T	RH	WB	DB
5.0	30.0	4.6	4.8
5.0	40.0	5.3	5.6
5.0	50.0	6.2	6.6
5.0	60.0	7.3	7.9

5.0	70.0	8.6	9.4
5.0	80.0	11.2	12.6
5.0	90.0	16.0	19.0
15.0	30.0	4.4	4.6
15.0	40.0	5.1	5.4
15.0	50.0	6.0	6.4
15.0	60.0	7.1	7.6
15.0	70.0	8.4	9.2
15.0	80.0	10.9	12.2
15.0	90.0	15.9	18.9
25.0	30.0	4.2	4.4
25.0	40.0	4.9	5.2
25.0	50.0	5.8	6.2
25.0	60.0	6.9	7.4
25.0	70.0	8.3	9.1
25.0	80.0	10.6	11.9
25.0	90.0	15.5	18.3
35.0	40.0	4.6	4.8
35.0	50.0	5.5	5.8
35.0	60.0	6.7	7.2
35.0	70.0	8.1	8.8
35.0	80.0	10.3	11.5
35.0	90.0	15.0	17.6

Tower - Desorption

5.0	30.0	5.1	5.4
5.0	40.0	5.7	6.0
5.0	50.0	6.7	7.2
5.0	60.0	7.8	8.5
5.0	70.0	9.1	10.0
5.0	80.0	11.2	12.6
5.0	90.0	16.0	19.0
15.0	30.0	5.0	5.3
15.0	40.0	5.5	5.8
15.0	50.0	6.5	7.0
15.0	60.0	7.6	8.2
15.0	70.0	8.9	9.8
15.0	80.0	10.9	12.2
15.0	90.0	16.0	19.0
25.0	30.0	4.6	4.8
25.0	40.0	5.3	5.6
25.0	50.0	6.2	6.6
25.0	60.0	7.3	7.9
25.0	70.0	8.6	9.4
25.0	80.0	10.6	11.9
25.0	90.0	15.5	18.3
35.0	40.0	5.0	5.3
35.0	50.0	5.9	6.3
35.0	60.0	6.9	7.4
35.0	70.0	8.3	9.1
35.0	80.0	10.4	11.6
35.0	90.0	15.2	17.9

Pixton & Henderson, 1981

Candle - Adsorption

5.0	46.5	6.0	6.4
5.0	65.0	8.0	8.7
5.0	76.0	10.0	11.1
5.0	82.3	12.0	13.6
5.0	86.7	14.0	16.3
5.0	89.7	16.0	19.0
5.0	91.5	18.0	22.0
15.0	48.7	6.0	6.4
15.0	66.0	8.0	8.7
15.0	76.5	10.0	11.1
15.0	83.0	12.0	13.6
15.0	87.5	14.0	16.3
15.0	90.0	16.0	19.0
15.0	91.7	18.0	22.0
25.0	50.5	6.0	6.4
25.0	67.3	8.0	8.7
25.0	77.3	10.0	11.1
25.0	83.5	12.0	13.6
25.0	88.0	14.0	16.3
25.0	90.2	16.0	19.0
25.0	92.0	18.0	22.0
35.0	52.5	6.0	6.4
35.0	68.7	8.0	8.7
35.0	78.8	10.0	11.1
35.0	84.0	12.0	13.6
35.0	88.3	14.0	16.3
35.0	90.5	16.0	19.0
35.0	92.3	18.0	22.0

Candle - Desorption

5.0	42.0	6.0	6.4
5.0	62.5	8.0	8.7
5.0	75.2	10.0	11.1
5.0	82.3	12.0	13.6
5.0	86.7	14.0	16.3
5.0	89.7	16.0	19.0
5.0	91.5	18.0	22.0
15.0	21.5	4.0	4.2
15.0	44.5	6.0	6.4
15.0	64.2	8.0	8.7
15.0	76.0	10.0	11.1
15.0	83.0	12.0	13.6
15.0	87.5	14.0	16.3
15.0	90.0	16.0	19.0
15.0	91.7	18.0	22.0
25.0	23.5	4.0	4.2
25.0	47.7	6.0	6.4
25.0	66.5	8.0	8.7
25.0	77.0	10.0	11.1
25.0	83.5	12.0	13.6
25.0	88.0	14.0	16.3
25.0	90.2	16.0	19.0
25.0	92.0	18.0	22.0
35.0	26.5	4.0	4.2
35.0	51.5	6.0	6.4
35.0	68.5	8.0	8.7
35.0	78.0	10.0	11.1
35.0	84.0	12.0	13.6
35.0	88.3	14.0	16.3
35.0	90.5	16.0	19.0
35.0	92.3	18.0	22.0

Henderson & Wilkin, 1985

Jet Neuf - Adsorption

5.0	32.3	4.4	4.6
5.0	48.9	5.9	6.3
5.0	66.0	8.0	8.7
5.0	79.0	10.5	11.7
5.0	84.9	14.8	17.4
15.0	34.8	4.4	4.6
15.0	49.6	5.9	6.3
15.0	68.3	8.0	8.7
15.0	79.3	10.5	11.7
15.0	87.2	14.8	17.4
25.0	36.4	4.4	4.6
25.0	51.7	5.9	6.3
25.0	69.4	8.0	8.7
25.0	80.0	10.5	11.7
25.0	88.6	14.8	17.4

Jet Neuf - Desorption

5.0	22.7	3.9	4.1
5.0	49.8	6.0	6.4
5.0	72.5	8.9	9.8
5.0	79.5	10.7	12.0
5.0	92.2	17.8	21.6
15.0	25.5	3.9	4.1
15.0	51.3	6.0	6.4
15.0	73.2	8.9	9.8
15.0	80.1	10.7	12.0
15.0	92.5	17.8	21.6
25.0	27.6	3.9	4.1
25.0	52.8	6.0	6.4
25.0	73.9	8.9	9.8
25.0	80.6	10.7	12.0
25.0	92.6	17.8	21.6

Bienvenu - Adsorption

5.0	39.9	5.1	5.3
5.0	54.8	6.3	6.7
5.0	66.2	7.7	8.3
5.0	80.0	10.6	11.9
5.0	86.5	14.8	17.3
15.0	42.4	5.1	5.3
15.0	56.7	6.3	6.7
15.0	67.5	7.7	8.3
15.0	80.6	10.6	11.9
15.0	88.2	14.8	17.3
25.0	44.4	5.1	5.3
25.0	58.4	6.3	6.7
25.0	68.8	7.7	8.3
25.0	81.0	10.6	11.9
25.0	89.0	14.8	17.3

Fiona - Adsorption

5.0	30.5	4.6	4.8
5.0	55.0	6.5	6.9
5.0	67.3	8.0	8.7
5.0	81.2	11.2	12.5
15.0	33.1	4.6	4.8
15.0	56.7	6.5	6.9
15.0	68.3	8.0	8.7
15.0	81.7	11.2	12.5
25.0	35.2	4.6	4.8
25.0	58.4	6.5	6.9
25.0	69.9	8.0	8.7
25.0	82.2	11.2	12.5

Sokhansanj et al., 1986

Tobin - Adsorption

4.5	18.0	4.8	5.0
4.6	37.0	6.1	6.5
4.7	53.0	7.6	8.2
4.7	66.0	9.5	10.5
4.8	75.0	11.6	13.1
5.1	89.0	15.7	18.6
10.1	47.0	6.1	6.5
10.4	54.0	7.4	7.9
9.8	64.0	8.5	9.3
10.2	79.0	10.8	12.1
10.0	87.0	14.9	17.6
10.0	90.0	16.0	19.0
15.4	30.0	4.9	5.1
15.5	38.0	6.0	6.4
14.9	55.0	7.4	8.0
14.9	71.0	9.7	10.7
15.1	79.0	11.8	13.4
15.5	83.0	14.2	16.6
20.0	32.0	4.8	5.0
19.6	55.0	7.5	8.1
20.5	76.0	10.3	11.5
19.8	78.0	11.3	12.7
20.5	86.0	13.9	16.1
20.3	88.0	15.8	18.8
24.8	42.0	5.9	6.3
25.0	64.0	7.9	8.6
24.7	74.0	9.5	10.5
24.5	83.0	11.7	13.2
24.3	88.0	14.3	16.7

Patil & Ward, 1989

Tower - Desorption

30.0	28.0	4.6	4.8
40.0	16.6	3.7	3.8
50.0	9.9	2.8	2.9
60.0	6.1	2.2	2.3

Sutherland & Ghaly, 1982

Desorption

40.0	16.6	4.0	4.2
50.0	9.9	2.8	2.9
60.0	6.1	2.1	2.1
65.0	4.9	1.8	1.8
70.0	3.9	1.5	1.5

Shatadal et al, 1989

Tobin - Adsorption

7.5	80.0	12.2	13.9
15.0	80.0	11.3	12.7
22.5	80.0	10.7	12.0
30.0	80.0	10.1	11.2
16.0	90.0	15.0	17.7
22.5	90.0	14.5	17.0
30.0	90.0	12.3	14.0

HGCA OILSEEDS RESEARCH REVIEW No. OS6

DRYING AND STORAGE OF OILSEED RAPE IN THE UK

PART II: PEST CONTROL OF STORED OILSEED RAPE

by

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TERMS OF REFERENCE

The present review seeks to summarise the information currently available on the infestability of stored oilseed rape and the difficulties of pest control. Additionally, outstanding problems, including those associated with newer varieties, are highlighted and areas where information is lacking are identified. It concludes with some recommendations for future research and development.

The review is aimed at the UK oilseed industry. However, during compilation of the review it became apparent that there was comparatively little scientific or technical data for oilseed rape in the UK. Therefore, extensive use was made of data from other countries, especially Canada and France. Also, some reliance has been placed on observational data collected by MAFF staff over a number of years.

Most of the information for this review has come from the comprehensive database of references held at the Central Science Laboratory, Slough, together with data from unpublished research undertaken at the same Laboratory. Computer searches of other databases have also been carried out, concentrating on references from the period 1970-1990. References referred to are listed at the end of this review.

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1. INTRODUCTION

The terms rapeseed and oilseed rape, as used in world commerce, is applied to 3 different species of the genus Brassica. B. campestris L. has a nearly world-wide distribution and is referred to as turnip rape, Polish rape, sarson or toria. B. napus L., mainly restricted to Europe and North America, is known as colza, swede rape or Argentine rape. Both of these species may also be described as either summer or winter rape depending on the specific cultivar. B. juncea L. is grown mainly in India and is known as brown, Indian or Oriental mustard. The name rape is derived from the Latin rapum meaning turnip. A fuller discussion of the nomenclature and botany of rapeseed is given in Appleqvist and Ohlson (1972). Most of the information in this review refers to B. campestris and B. napus.

Historical records suggest that rapeseed was being cultivated in India as early as 2000 BC but large scale production in Europe did not begin until the 13th century AD. During the Middle Ages rape oil was the most important lamp oil in northern Europe. In the 17th century there was a seed-crushing industry in Britain which met home demand and produced a surplus for export. The oil was mainly used for lighting, and only the poor used it as an edible oil. As other vegetable oils became available towards the end of the 19th century, rapeseed declined in importance in Western Europe, and it was not until there was a demand for special lubricating oils during the second world war that interest in rapeseed was stimulated again.

However, the greatest boost to production in EC countries began in the 1970's when political considerations resulted in the introduction of an intervention price structure for rapeseed designed to reduce the dependency of the EC on imported vegetable oils and proteins. Production has continued to rise until today it is Europe's most important source of vegetable oil. The oil is used in the manufacture of margarines, cooking fats, soap, synthetic rubber and as a lubricant. Rapeseed oil has also been used as a repellent to protect stored seeds against storage insects (Ediz and Davis, 1980; Shukla et al., 1988). Rapeseed meal, a high protein by-product of oil extraction, is used in animal feeds. Oilseed rape is also a useful break crop in cereal production (Green, 1981). Further historical details are given by Appleqvist and Ohlson (1972) and Weiss (1983).

The rapid expansion in rapeseed production detailed above has also occurred worldwide in recent years. In 1988/89, 23 million tonnes were produced, the third highest figure for any oilseed after soybean and sunflower seed (Anon., 1990). Canada was the largest producer and exporter, the other main producers being Northern Europe, Pakistan, Bangladesh and China. During the same period, France was the largest producer in the EC (Anon., 1990a). Latest figures reveal that EC production has risen from 4.97 million tonnes in 1989 to an estimated 5.84 million tonnes in 1990, an increase of over

18% (Anon.,1991a).

Largely as a result of EC price incentives, rapeseed production in the UK continues to rise, from 12,000 tonnes in 1969 to 0.98 million tonnes in 1989. A further 26% increase to 1.23 million tonnes was forecast for 1990, mainly for use at home but with 193,000 tonnes going for export (Anon., 1991a).

Originally rapeseed oil was used mainly for industry and domestic lighting because it contained high levels of the toxic compound erucic acid which made it less suitable for human consumption. The expeller or meal left after the oil had been extracted also contained toxic compounds in the form of glucosinolates, which greatly restricted the rate of inclusion in animal feed. Both these chemicals occur naturally in the seeds of many Brassicas and have, almost certainly, evolved as chemical protectants against attack by arthropods or vertebrates. Erucic acid has been associated with coronary heart disease in humans, although the low levels consumed in margarines and cooking fats are thought unlikely to have any significant effects (Nash, 1985). Rapeseed meal contained levels of glucosinolates that produced unacceptable side effects in some species of livestock, thus rendering the meal unsuitable as animal feed. These included reduced palatability of feed for pigs and calves, effects on the thyroid in most stock,liver haemorrhage and lowering of productivity in hens (Anon.,1985).

More recently, however, plant breeders have developed varieties with low levels of both erucic acid and glucosinolates. These "double low" varieties have enhanced the attractiveness of rapeseed as a source of edible oil for human consumption and as a protein rich animal feed (Weiss, 1983). "Double low" varieties are also known as "Canola" in Canada where it is a trademark of the Canola Council of Canada and refers to seed, oil and meal from varieties of B.campestris and B. napus which have less than 5% erucic acid and less than 30 micrograms of glucosinolates (as 3-butenyl isothiocyanate) per gram of seed (White and Nowicki, 1985). All the varieties currently recommended by the National Institute of Agricultural Botany for use in England and Wales are of the "double low" type and yield seed with oil contents approaching 45% at a standard 9% moisture content (Anon., 1991). A small amount of seed with a high erucic acid content is grown in the UK and is also imported for the manufacture of lubricants with special properties.

As well as the change to double low varieties, in the UK there has been a switch from spring to winter varieties, mainly due to their higher yields, better resistance to weather fluctuations and their suitability for crop rotation. Winter varieties of B. napus now account for over 96% of the national rapeseed crop, estimated as in excess of 390,000 hectares for 1990 (Anon., 1991).

As a result of increased production, more rapeseed is being stored in this country, and storage periods have had to be

extended, both on the farm and in commercial stores. The size of individual bulks being stored has also increased, adding to the potential for storage problems.

It is feasible to store rapeseed for long periods. However, it must be realised that there are large differences in equilibrium relative humidity (erh) between rapeseed and cereal grains. For example, the equilibrium moisture content for rape is much lower than for cereals at any given relative humidity and temperature combination. Rates of respiration are also much greater at low erh in rape than in wheat (Nash, 1985). If the moisture and heat of respiration are not quickly removed, moulding and heating will soon take place, leading to a marked increase in the level of free fatty acids in these high oil content seeds (Nash, 1985). Thus, rapeseed needs to be dried to a very low moisture content (less than 8%) as soon as possible after harvest, but not much below 7% because this causes the seeds to become fragile and likely to crack when mechanically handled. Broken seed is more likely to become infested with storage pests. Another problem is that the small size of rape seeds enables them to pack together more tightly, thereby increasing air resistance during drying or cooling operations compared to that for cereals. Thus, a bulk drying system designed to dry wheat would require a longer period of operation to dry a similar bulk of rapeseed. In practice, the capacity of such systems is usually reduced to avoid prolonged periods of drying.

During the early years of expansion in the UK rape crop, serious problems caused by mites and fungi were common. As farmers and storekeepers gained experience the frequency of these problems was reduced by better drying before storage and the use of contact pesticides. However, despite these improved storage practices, mite infestations continued to present problems. Some of the difficulties can be attributed to the use and interpretation of the readings from electrical moisture meters. The accuracy of these instruments and the lack of precise information on safe storage moisture contents for the newer rapeseed varieties, together with a trading limit of about 9% moisture content, would appear to be the main reasons for these continuing problems.

Although mites are the current major storage problem, reports of insect infestations have also been increasing over the past few years. Although further research is required, initial studies at the Central Science Laboratory, Slough, indicated that some of the newer varieties may be more susceptible to insect attack than others, perhaps as a result of the reductions in erucic acid and glucosinolate levels (Amos, 1990).Further information is also required about the species and frequency of infestation of stored rapeseed. Recent surveys of farm and commercial stores in the UK by MAFF did not include rapeseed.

As well as the storage problems outlined above, in recent years there has been a general demand for higher standards of pest-free stored products coupled with an increasing desire to reduce the use of pesticides on products destined for

human consumption. This in turn has led to renewed interest in non-chemical methods of pest prevention and control.

There is very little published information on stored oilseed rape compared to that on stored cereals. Furthermore, there has been very little work on the storage of rapeseed undertaken in the UK compared to other countries. Past research on the storage of rapeseed in the UK has always been of a limited and restricted nature. As a result, many of the recommendations used today are flawed. The simple economics of storage force the use of prophylactic pesticides. If their use was restricted, in line with EC proposals, the options available to avoid storage infestations would be limited to the use of physical control measures, few of which are as cheap, easy to use or as effective as pesticides.

2. INFESTABILITY

2.1 Introduction

In common with other plant seeds, oilseed rape provides a potentially attractive source of nutrients for many living organisms as well as for humans. The harvested and stored seed can be attacked by rodents, birds, insects, mites and micro-organisms, providing factors such as the physical conditions of the seed and its environment are suitable (Section 2.2). However, the ability of rodents and birds to damage rapeseed is severely restricted by bulk storage structures whereas insects, mites and fungi may be favoured by large masses of seed. The ability of pests to attack rapeseed may also be affected by the chemical composition of the seed which in turn is dependent on factors such as seed variety, growing season and time of harvesting. All of these factors may alter the levels of toxins and attractants present in the seed. The size and convexity of the seed together with the toughness, thickness and smoothness of the seed coat may also limit the attack and subsequent development of infestation. The presence of dust and dockage, including fractured and broken seeds produced during harvesting and cleaning, will also affect the progress of an infestation. Thus, some invertebrates that are unable to survive on whole, undamaged rapeseed may be able to develop on crushed seed or rapeseed meal.

The main infestation problems affecting stored oilseed rape in cool temperate climates, such as the U.K., are mites and fungi, although insects and rodents can also be troublesome on occasions. For example, in the U.K. over the last 4 years there have been several reports of insect infestations in stored rapeseed (Section 2.3).

The consequences of infestation are considerable, both for the farmer and processor as well as the consumer. Farmers

run the risk of having their seed rejected if they fail to meet the "pest-free" standards imposed by export contracts and IBAP. Even the presence of a few beneficial predatory insects or mites may lead to the rejection of an entire bulk in some circumstances. The farmer will then have to use costly control measures and may experience cash flow problems. Insect and mite fragments can cause respiratory and other allergic reactions during handling of the seed. These, coupled with moulds and mycotoxins represent health threats to farm workers handling mouldy seed, while seed contaminated with rodent urine can spread diseases such as Leptospirosis. Heavy infestations will lead to weight loss and reduced germination potential in seed destined for sowing. Damp, mouldy seed is difficult to handle due to clumping, and in extreme cases heating in mouldy seed may be sufficient to start a fire. The consequences of infestation for the oil crushers and processors can be expensive delays in production as well as other financial losses due to the unknown effects on oil quality. For example, the lipolytic (i.e. capable of breaking down oil)activity of storage fungi can produce high levels of free fatty acids which can break down rapeseed oil (Section 2.5). In many such cases the commercial value of the rapeseed will be lowered considerably. Crushers and processors are also concerned about the possible carry over of residues of pesticide used to control infestations into the processed oil and meal. The consumer can also be affected by infestations which may increase the price of the end product and possibly even reduce its quality and palatability. Consumers are increasingly concerned about the safety of food, so that the presence of pesticide residues resulting from attempts to control infestation,and mycotoxins carried over from mouldy stored products could affect the saleability of the oil.

2.2 Effects of physical properties

Two of the most important factors affecting infestability of oilseed rape by storage pests are the equilibrium relative humidity (erh) and temperature, erh being defined as the relative humidity, of the intergranular air in the seed bulk, with which the seed is in equilibrium at a given moisture content and temperature. Wilkin (1986) quotes two general rules: firstly that mites and moulds need relative humidities above 65% and preferably above 75% for development, but are not very dependent on high temperatures, and secondly that most storage pest insects need temperatures of 18°C and above to develop but are less constrained by humidity. It is erh rather than the moisture content (mc) of a product that is critical for pest development but the erh in the intergranular spaces is controlled by the mc and temperature. The relationship between mc, erh and temperature is discussed in section 3.8.

Oilseed rape is hygroscopic and surface layers of a bulk dried to below 7.5% mc can pick up sufficient moisture from the atmosphere for mites to develop. It is also a good insulator and heat does not, therefore, disperse easily. The thermal conductivity of oilseed rape is lower than for other grains, probably due to the spherical shape of the seed (Moysey et al., 1977). If the seed is put into the store warm, or the temperature is raised by drying, these conditions may encourage mites, micro-organisms and insects. Convection currents in the warm seed will carry moisture upwards which will condense in the cooler surface layers. The resultant high water activity will lead to ideal conditions for fungal growth and/or mite development. Once pests start to develop, the metabolic heat and water produced escalate the problem, and hot-spots soon develop. Heat-damaged seed has a low viability, tobacco-like odour, low pH in deionised water, a high fat acidity value and is typically darker in colour (Mills and Kim, 1977).

Sinha and Wallace (1977) observed that mycophagous mites, predatory mites and Penicillium spp. often increase as rapeseed quality deteriorates; their development is related to the presence of dockage which, if excessive, can lead to an explosive multiplication of Acarus spp. mites.

Appleqvist and Loof (1972) observed a more rapid increase in free fatty acid levels and microflora in cracked seeds and seed fragments compared to intact ones. Drying to a mc of 7-8%, the level recommended for safe storage, is unlikely to lead to increased fragility, damage or dockage. Fragility increases only slightly with decreasing mc down to 6% but increases more rapidly below this. Green (1981), however, reported that conveyors can damage seed dried to below 7% mc.

Oilseed rape is a small seed with an average size of 2mm. This is too small to accommodate the larvae of insects such as the grain weevil, Sitophilus granarius, and the lesser grain borer, Rhyzopertha dominica, that develop inside grains, and Amos (1990) found that these species did not develop in oilseed rape (see section 2.3).

The bulk density of rapeseed decreases with increasing mc, and porosity increases with increasing mc (Jayas et al, 1989). There is no evidence to suggest that bulk density affects infestability directly, although a decrease in bulk density may increase the thermal conductivity and specific heat (Moysey et al, 1977) and coupled with an increase in mc, this could create favourable conditions for pest infestation.

The seed coat puncture resistance of both dry and moist (0 and 70% erh) rapeseed is significantly lower than the corresponding values for wheat, oats and barley (Sinha and Voisey, 1978). The tests are believed to approximate to seed coat penetration by weevils infesting stored seed, and

also show that moist seeds are significantly less resistant to puncture than dry seed.

2.3 Insects

In the past, insect infestation was not considered to be a problem with UK farm-stored rapeseed but more recently there have been a number of incidences of beetles in the genera Cryptolestes and Typhaea infesting the stored commodity. Larvae of the white-shouldered house moth, Endrosis sarcitrella, can also occur in fairly large numbers in rapeseed in the UK, clumping the seeds together near the upper surface and sides of a bulk (Anon., 1981).

In Canada, Sinha and Wallace (1977) found that the rust-red grain beetle, Cryptolestes ferrugineus, and Psocoptera were common on rapeseed stored in farm bins, while Sinha et al.(1981) reported sparse infestations of the black carpet beetle, Attagenus unicolor.

There is only a limited amount of information published on the susceptibility of oilseed rape to insect attack during storage, and most of this has been carried out in Canada using Canadian varieties. From the results, there is evidence to suggest that the merchant grain beetle, Oryzaephilus mercator, in particular can survive and reproduce on rapeseed (Sinha, 1972; 1976). In choice tests, rapeseed was chosen by O. mercator adults in preference to groundnut, sunflower or soya bean seeds (Verner, 1971). In another choice test, contradictory results were obtained, and few O. mercator adults chose whole rapeseed, preferring commodities such as bran, shelled sunflower seeds and rolled oats (Loschiavo,1976); however, the rapeseed variety used was high in glucosinolates and the adults were previously reared on cereal products rather than rapeseed. Other work shows that although the rust-red flour beetle, Tribolium castaneum, can survive on the seed (Sinha, 1976), the life-cycle is considerably extended, with few larvae ever developing into adults (Pierre and Delion, 1973). Sinha (1972) showed that the confused flour beetle, Tribolium confusum, T. castaneum, the saw-toothed grain beetle, Oryzaephilus surinamensis and O. mercator but not C. ferrugineus could complete development on some varieties of crushed rapeseed.

S. granarius, S.oryzae, and R. dominica do not represent a threat to stored oilseed rape; the larvae of the weevils and the pupae of the grain borer develop inside grains, and rapeseeds are too small to accommodate these developmental stages (Pierre and Delion, 1973).

As well as E. sarcitrella, other moth species are known to

infest oilseed rape, particularly the tropical warehouse moth, Ephestia cautella, the Indian meal moth, Plodia interpunctella, and the rice moth, Corcyra cephalonica (Table 1). The larvae of these species are also capable of producing dense silk webbing which can clog machinery during movement and processing of the commodity (Cox and Bell, 1985).

Tests have been carried out at CSL, Slough, using some of the "Double Low" varieties of oilseed rape to determine whether the different chemical composition of these newer varieties would influence their susceptibility to attack by insect pests. The results showed that adults of both C. ferrugineus and O. surinamensis could survive for up to two and four months respectively, although only O. surinamensis was able to multiply on the seed (Amos, 1990). Adults of T. castaneum showed a higher degree of survival and breeding although, as in the work of Pierre and Delion (1973), rarely did all the larvae produced develop into adults. In all these tests the insect survival rate was always greater on samples containing broken seed. Differences in survival and breeding rates between the varieties do suggest that certain varieties lack some essential requirements for insect development (Amos, 1990).

Occasionally rapeseed has been infested deliberately to evaluate the nutritional quality of new varieties. Larvae of the yellow mealworm beetle, Tenebrio molitor, have been used to compare the nutritional quality of different varieties of rapeseed (Anon., 1985; Pracos, 1983) and rapeseed meal (Davis and Sosulski, 1972). For example, dry weight losses of 111mg/larvae over 28 days were recorded for the "Regent" variety. Davis et al. (1983) demonstrated that T. molitor larvae attained a much higher weight on seeds of "Canola" (i.e. "double low" rapeseed) cultivars than on older varieties of rapeseed.

There appears to be no information on the infestation of UK expeller but in India Brar et al.(1987) noted that samples of rapeseed cake from grain markets in the Punjab were frequently infested with T. castaneum and O. surinamensis. The rice weevil, Sitophilus oryzae, and the khapra beetle, Trogoderma granarium, were also found in some samples. In the UK, MAFF ship inspections during the 1970's regularly intercepted E. cautella on rapeseed meal from the Indian sub-continent.

Recently, the survival and development of 15 storage insect species were tested on Canola meal in laboratory cultures by White and Jayas (1989). Only Tribolium spp. survived and multiplied on the meal when left for 3 months at 30°C, 65% rh., confirming that, although they are potential pests of this product, infestations would not be as severe as in cereal products. These results are in contrast to similar work on another oilseed product, soya bean meal, where 12 insect species were able to complete development and

multiply (Cox and Simms, 1978).

Thus, some insect pests can survive and breed on stored rape, particularly on specific varieties, but do so at a low rate. Therefore, serious problems during short term storage are unlikely. In some cases, infestations may only be temporary; the insects probably feeding on residues from the previous storage of cereals. However, it is possible that the bulks of rapeseed could provide a reservoir of insects that could migrate into other, more infestable crops stored nearby.

2.4 Mites

Although mites are small (<0.5mm), they can cause serious damage to stored rapeseed and their presence will lead to rejection of the seed by the crushers (Wilkin, 1986). In a survey of stored rapeseed on 27 UK farms mites were commonly found and sometimes presented a serious problem, very heavy surface infestations being recorded on 3 farms (Anon., 1975).

Mite infestations have been reported from other Western European countries such as France (Fleurat- Lessard, 1974) and Denmark (Anon., 1985), and from Canada (Mills, 1976) but they seem to be particularly important in the UK where, even if the seed is initially dried to a safe moisture content, it tends to reabsorb atmospheric moisture during storage (Good et al., 1977).

In England, the commonest species of mites occurring on stored rapeseed are the flour mite, Acarus siro and the cosmopolitan food mite, Glycyphagus destructor (Armitage, 1980). Fleurat- Lessard and Anglade (1973) suggested that the most important species in France was the mould mite, Tyrophagus putrescentiae. In Denmark, nearly all the mites found in samples of rapeseed were A. siro, together with a few Tyrophagus dimidiatus, G. destructor and tarsonemid mites (Anon., 1985). In Canada, Sinha and Wallace (1977) found Acarus immobilis and A. siro as well as G. destructor and the predators Blattisocius keegani and Cheyletus eruditus (Table 2).

Concentrations of 23,000 mites/kg, mainly A. siro, were found at the surface of a bin of rapeseed in the UK where the moisture content rose from 8% to 9.5% (Good et al., 1977). Armitage (1980) found G. destructor predominated in rapeseed at about 8% mc, reaching maximum numbers of 3,500 mites/kg, while A. siro predominated at 9% mc and exceeded 50,000/kg. Stables (1975) surveyed 14 UK farms after the completion of rapeseed drying, and in one case an infestation of about 80,000 mites/kg was detected in surface seed. Concentrations of mites as high as one million/kg at moisture contents of 13-14% have been recorded in Denmark (Anon., 1985). Pierre (1974) classed infestations of 4,000 mites/kg as slight and 40,000 /kg as

Table 1. Insect pests of stored oilseed rape.

Pests in UK	Potential pests in UK	Pests elsewhere
E. sarcitrella	Cryptolestes spp	O. mercator
	Typhaea stercorea	E. cautella
	O. surinamensis	P.interpunctella
	T. castaneum	C. cephalonica

Table 2. Mite pests of stored oilseed rape.

Pests in UK	Pests elsewhere with potential in UK
A. siro	A. immobilis
G. destructor	T. putrescentiae
	T. dimidiatus

severe.

In rapeseed, mites feed on and hollow out seeds that have been damaged either by handling during harvesting and drying (Armitage, 1980) or by fungi (Pierre and Fleurat Lessard, 1973). Mills et al. (1978) found that mites were not associated with an increase in fatty acid values, suggesting that they do not directly degrade the fat component of the rapeseed. However, other reports claimed that mite damage leaves the oily content of the seed open to attack by oxygen and micro-organisms (Anon., 1968). Large numbers of mites may taint the seed and make it less acceptable to the crushers. Mites are also powerful allergens and contact with infested seed may present a health hazard to handlers.

Both A. siro and G. destructor can only develop in seed with a moisture content of more than 8% and do not usually cause problems below 8.5% (Wilkin, 1983). However, this moisture content will be dependent on the erh of specific varieties and the temperature of the seed. These mites can survive at temperatures below zero and still breed at 5°C but their optimum temperature for population increase is about 25°C (Cunnington, 1976). At this temperature A. siro and G. destructor can increase by up to 7 and 4 times/week, respectively (Cunnington, 1984; 1985). This rapid rate of build up and the difficulty in detecting small numbers of mites mean that heavy infestations may occur without warning, and become obvious only when the mites reach such numbers that they cover a bulk of seed with a fine brown dust (Wilkin, 1983).

2.5 Fungi

Fungi are responsible for some of the main problems associated with the storage of rapeseed in the UK (Anon., 1975). The development of fungi results in seed being bound together, making subsequent handling difficult and dangerous. Serious fungal development will cause heating and ultimately result in the oil being broken down into free fatty acids with a loss in quality and attendant risk of corrosion of metal storage bins. Mouldy seed may be rejected by the crushers, and in severe cases of heating, entire stores have been destroyed because the seed caught fire (Wilkin, 1986). Mouldy rapeseed represents a serious hazard to handlers since repeated inhalation of fungal spores sensitises individuals and can cause allergic reactions. Some fungi may also produce mycotoxins which render meal produced from affected seed unsuitable for animal feed. It is not known if mycotoxins are found in the refined oil.

Far more studies have been carried out on the fungi associated with stored cereals than with rapeseed. In connection with cereals, Christensen (1957) developed the

concept of "field" and "storage" fungi. The field fungi are abundant on seeds at harvest and rarely proliferate during storage while the storage fungi are present in very low numbers on freshly harvested seed but are the species that subsequently grow in storage. Cladosporium appears to be the most abundant field species in rapeseed while Alternaria holds that place for cereals (Sinha and Wallace, 1977). However, in stored rapeseed Aspergillus and Penicillium are the predominant genera, as they are in cereals. In special circumstances such as heating, other storage fungi such as Absidia ramosa and Mucor pusillus can occur (Mills and Bollen, 1976), along with thermophilic actinomycetes (Anon, 1978).

In the UK, Burrell et al. (1980) studied the two main factors, moisture content and temperature, that affect fungal growth in stored rapeseed. The time taken for the spoilage of freshly harvested rapeseed stored aerobically was measured at moisture contents between 6 and 17% and temperatures from 5 to 25°C over a storage period of 35 weeks. At the lowest moisture no visible fungal growth occurred at any temperature. Conversely, at the highest moisture level visible moulding occurred within 5 days at the highest temperature. At 9% moisture, no growth was detected after 300 days at 5 and 10°C; it took 256 days to appear at 15°C but only 90 days at 25°C. They reported that fungi of the Aspergillus glaucus (Eurotium) and A. restrictus groups occurred at the lower moisture contents while A. candidus and Penicillium spp. were found at moistures above 10%.

In a similar study in Canada, Mills and Sinha (1980) confirmed that Aspergillus glaucus group and Penicillium spp. were the most abundant in stored rapeseed. At the highest moisture, Penicillium developed from nearly 100% of the seed after about 30 days storage. They also presented a table predicting where spoilage would occur at different moisture content/temperature combinations typical of northern continental climatic zones.

These studies confirm that fungal growth in rapeseed starts at moisture levels appreciably below that at which it starts in cereals.

However, there appear to be no studies on the semi-airtight storage of moist rapeseed, similar to those on cereals by Clarke and Hill (1981).

The breaking down of oil into free fatty acids (FFA) is undesirable from the viewpoint of the downgrading of the oil but also because some FFAs produce undesirable off odours and taints. Mills and Sinha (1980) found that at the low moisture of 7% there was little increase in fat acidity value (FAV) or growth of fungi. But, at moisture contents of about 9-12%, FAV increased steadily and so did the counts of A. glaucus (Eurotium) and Penicillium species.

In the UK, Azzabi et al. (1981) found that out of 18 species tested all were lipolytic in rapeseed oil except Aspergillus versicolor. Mondal and Nandi (1984) inoculated rapeseed of 20% moisture with pure cultures of four Aspergillus species. After 30 days incubation at 30°C, A. niger caused the largest increase in FAV followed by A. fumigatus and A. funiculosus, with A. chevalieri causing the least change. There is, therefore, considerable potential for deterioration of the oil when rapeseed has been attacked by storage fungi.

Our knowledge of the occurrence of mycotoxins in stored cereals is again considerably greater than that in stored rapeseed. Even the one main study (Mills and Abramson, 1982) on the potential for production of the mycotoxin, ochratoxin A, among isolates of Penicillium species from rapeseed used moist barley meal as the test substrate instead of rapeseed. Seven out of the 34 chosen isolates of Penicillium produced ochratoxin A. In another study in Scotland McKenzie et al. (1988) found that three species of Alternaria isolated from rapeseed produced in varying amounts the mycotoxins alternariol, alternariol monomethyl ether and tentoxin on a V8 culture medium in the laboratory. However, no clear evidence was obtained of these mycotoxins being produced in the seed itself. White and Jayas (1989) studied infestation of canola meal by fungi but mycotoxin analysis was not carried out. So far there has been only one case of mycotoxins being found in UK farm stored rapeseed. This was in 1985 when the mycotoxins citrinin and sterigmatocystin were detected (MAFF, unpublished). Sterigmatocystin has been found to be carcinogenic to laboratory animals (Purchase and Van der Watt, 1970). However, it must be pointed out that very few samples of oilseed rape have been analysed by MAFF for mycotoxins.

2.6 Rodents

Infestations of stored oilseed rape by either the house mouse, Mus domesticus, or the brown rat, Rattus norvegicus, appear to be rare, although it is estimated that 53% and 59% of farm grain stores in the UK are infested by rats and mice, respectively (MAFF unpublished). Nevertheless, while stored rapeseed may not be particularly attractive to rodents and indeed may lack important nutritional requirements (Amiot et al., 1987), it is likely that problems will arise occasionally especially when oilseed rape is stored in association with grain. Rodent infestations are likely to be detected by finding the signs that rats and mice leave, such as smears, footprints and droppings, rather than seeing the animals themselves.

Given the potential threat to human and animal health, in addition to any economic damage and spoilage, rodent infestations should be dealt with as soon as they are detected.

3. PEST CONTROL

3.1 Introduction

During storage oilseed rape is susceptible to attack from a range of organisms (see Section 2). As a result, various control measures have been evolved. Much of the basic development of storage methods was carried out in other countries that have a longer history of large scale storage of oilseeds than in the U.K. However, over the past 10 years as the U.K. crop has increased, pest problems that are either specific to this country or are more acute because of our climate, have demanded the development of appropriate control measures. Unfortunately, the effort that has been expended on the development of these measures reflects the minor crop nature of oilseeds and the reduction in government support for research that occurred over the period.

In general, the main current storage problems can be divided into two categories:-

i) growth of fungi,

ii) development of mites.

The development of both of the above problems are dependent on the availability of water within the seeds and their intergranular spaces. This, in turn, is related to the moisture content and temperature of the seed. Therefore, these physical parameters are of fundamental importance to safe storage. Unfortunately, there is considerable commercial pressure on storers of seed to use moisture contents that are well above the minimum needs for the development of mites and fungi. For example, the current U.K. trading standard for oilseed rape is 9% moisture, at which level, given a temperature above 5°C, many fungi and all mite pests can develop. This trading standard encourages storekeepers to hold seed at close to 9%, thus maximising the weight of seed sold and minimising drying costs. The situation is further complicated by a lack of information on what is the maximum safe moisture content for long-term storage of oilseed rape and the difficulties in rapid moisture measurement (see Sections 3.8 and 4.4).

Post-harvest cooling is a technique that is being used very successfully in cereal storage to control insects, limit mites and minimise the need for pesticides. However, there is a complete lack of data on the application of this approach to oilseed rape.

The above difficulties relating to physical methods have led to alternative chemical methods being adopted, representing procedures that are unique to the U.K. Chemical control options currently available include the use of contact pesticides to

treat the store or to apply directly to the seed and the use of gaseous fumigants. Of these options, direct admixture of a pesticide with the seed is by far the most frequently used method with at least 60% of the U.K. crop being treated during storage (Sly, 1986).

The reasons for using some form of physical or chemical techniques during storage vary. In most years the seed is harvested at a moisture content that is sufficiently high to encourage rapid fungal growth. In these circumstances, immediate drying is essential if total loss of the crop is to be prevented. However, the precise moisture content to which seed is dried may vary considerably between individual producers and storers, depending upon the equipment available, the likely storage period and the opinion of the individual. The treatment of the seed with a pesticide is carried out to control or prevent mite infestation and the high level of pesticide usage confirms that this pest poses a serious threat during storage. Fumigation is relatively expensive and disruptive, so is generally used as a technique of last resort to deal with serious mite infestations just before the sale of seed.

A further complication with the use of control measures is that mites are very small and, therefore, difficult to detect. Hence, the sudden discovery of serious infestations is a relatively common event. This, in turn, can encourage farmers and storekeepers to regard the routine application of pesticides as the best method of avoiding problems with mites during storage. Although some information on frequency of occurrence is available, there is a serious lack of data concerning the relative importance of the various species of mites found in stored seed and this hampers the introduction of a proper system of pest management.

3.2 Fabric treatment

There is clear separation between pest and disease problems in the field and those occurring during storage. The mites and fungi that present the major problems after harvest are, almost without exception, not found on the growing crop. Work on cereals (Griffiths, 1960; 1964) indicated that the principle storage pest mites, Acarus siro and Glycyphagus destructor, could not be found on growing crops. The suggestion was that these species of mite had evolved to take advantage of a "nest" environment. Similar data are available to indicate that counts of field fungi reduce rapidly during storage and are replaced by storage species, given suitable conditions for fungal development (see Section 2.5).

The above information indicates that at harvest oilseed rape is probably free from most of the organisms that are likely to cause damage during storage and that the seed becomes infected with fungi and infested with mites from the storage structure. Thus, decontamination of the store must offer an opportunity to reduce or eliminate damage during storage. This is the principle on which the techniques of store hygiene and treatment are based. The empty store is cleaned before harvest and then sprayed with a residual pesticide that has good activity against mites. There are no comparable chemical control methods that can be applied against fungi.

Very little, if any, research has been carried out to assess the effectiveness of the approach in protecting oilseed rape from mites and moulds during storage. Work with stored wheat suggested that thorough cleaning of the store followed by treatment of the structure with a pesticide may have delayed the occurrence of mite infestation (Anon., 1967). However, after a few months' storage, mites were introduced to the grain, probably by rodents.

The size of mites and the tendency of G. destructor to form hypopi (a resistant stage), must militate against the elimination of infestation by cleaning. Several pesticides are effective against stored product mites (see Section 3.3) and their use on the fabric of buildings must kill part of the residual mite population in a store. However, observations in empty stores indicate that mites tend to penetrate deep into any structural defects and thus may escape contact with a pesticide (Anon., 1975a). This data, together with other field observations, suggests that there is only limited value, in terms of restricting mite infestation in stored oilseed rape, from treating the fabric of the store with a pesticide.

There are no data on the use of chemicals to treat the fabric of a grain store against fungal spores.However, it is suspected that the same constraints would apply to treatments against fungi as have been detailed for mites.Even if a system of hygiene and treatment could be devised to control all mites and fungal spores within an empty store, the likelihood of the re-introduction via wind blown spores or mites transported by rodents or birds, must severely limit the cost-effectiveness of such an approach.

3.3 **Admixture**

The admixture of a pesticide directly with a cereal grain to deal with infestation, is a well established technique which was extensively reviewed in Wilkin and Rowlands (1988) and Rowlands et al,(1989). The system of applying a pesticide directly to the food medium of the pest has many attractions but requires pesticides that are sufficiently non-toxic to mammals to allow their direct application to a food-stuff. The method was only widely adopted for use on cereals when the organophosphorus (OP) pesticide malathion first became available in the late '50s and early '60s. This chemical was active against a wide range of insects which feed on stored grain and yet had a sufficiently low mammalian toxicity (about 2500 mg/kg, rat oral) to allow its application to grain at a dose that would not only disinfest but also give a minimum of several weeks protection from reinfestation (Green and Tyler, 1966).

Over the past 20 years, a range of second generation, OP pesticides have been developed. These compounds have similar mammalian toxicity characteristics to malathion but have better persistence and a wider spectrum of activity against grain pests (Tyler and Binns, 1977). As a result, the technique of admixing a pesticide with grain at the start of storage became one of the most widely used methods of protecting grain from insect attack in many parts of the world.

Several of the more recent OP grain protectants are active against important stored-product mite pests (Wilkin and Hope, 1973). This feature offered the potential for the use of such chemicals on oilseed rape to control mite infestations during storage. Work reported by Good et al (1977) showed that various pesticides could be used to control mites on oilseed rape but that the dose required was double that for cereal grains. The higher dose was necessary because the activity of a pesticide admixed with a commodity is related to its toxicity to the pest species and the dose that is available to the pest after the chemical has been applied. The smaller the diameter of the seed that is treated, the greater the surface area to volume ratio and, therefore, the greater the surface area over which a given dose of pesticide must be spread. A possible additional reason for this higher dose could be related to the solubility of OP pesticides in oil which might allow rapid diffusion into the seed.

Pesticides such as chlorpyrifos-methyl, etrimfos, methacrifos and pirimiphos-methyl have acaricidal properties, but the dose needed to kill stored product mites is, in general, greater than that needed to kill insect pests. The application rate of a pesticide to a food-stuff has to be fixed by a combination of its mammalian toxicity and the level of residues that are likely to result from a treatment,limiting the maximum possible application rate, and the dose needed to give control. Laboratory and field trials, carried out almost exclusively in the U.K., show that pesticide admixture can be used to control mites in oilseed rape

if the application rate is double that applied to cereal grains.

Currently in the U.K. only the following pesticides are approved for the treatment of stored oilseed rape under the Control of Pesticide regulations:

Etrimfos,

Pirimiphos-methyl.

Both chemicals are available as emulsifiable concentrates and dust formulations. They are widely used in the U.K., and the most recent data available from the 1980-83 MAFF Pesticide Usage Survey suggest that at least 60% of the crop is treated with one or other of these chemicals during storage (Sly, 1986). However, this situation does not appear to occur in any other country. The approval of only two of the six pesticides currently approved for use on cereal grains would appear to be more to do with commercial factors than toxicity or efficacy.

Detailed data on the efficacy of adding pesticides to oilseed rape are very limited. Good et al.(1977) give details of a large scale trial in which a 60-tonne bulk of oilseed was both disinfested and protected from further mite infestation over a six month storage period by an application of etrimfos at 10mg/kg. The control seed became very heavily infested over the same period. Other trials carried out at the Central Science Laboratory, Slough, but which are not published, confirmed that both of the pesticides approved for oilseed rape and one approved only for cereals will all reduce the numbers of mites developing in seed during storage but that double the dose used to treat cereal grains is needed.

The pesticides applied to oilseed rape during storage offer protection from infestation over a period of several months. This is achieved because the pesticide persists on the seed during storage. Some decay may occur, although results from Good et al.(1977) demonstrated no decline in etrimfos residues over a 6-month storage period. Therefore, a consequence of the use of the admixture method is likely to be that some pesticide reaches the production process and there is a risk that it may pass through into the finished oil and expeller. This is discussed in more detail in Section 3.4.

The widespread use of admixture by farmers and storekeepers in the U.K. suggests that the method is both effective and necessary. The necessity of use is probably related to the current trading limit for moisture of 9%. Storage at close to this level would encourage mites (see Section 3.8) but reducing the moisture content to a safe storage level would increase the drying costs and reduce the weight of seed marketed by the farmer. Assuming a harvest of 1 million tonnes, drying costs to reduce its moisture content by 1.5% must be at least £1.5 - 3 million and the loss in weight would cost perhaps £4 million. Therefore, the total saving that is currently being achieved by

the growers of rapeseed by using pesticides is more than £5 million.

As stated earlier, the pesticides approved for admixture with oilseed rape in the U.K. are available formulated as dusts or emulsifiable concentrates. The latter must be diluted in water before application and then sprayed on the seed, while the former are supplied in "ready-to-use" form.

The normal method of applying a pesticide to a grain or seed is to convey the product and apply the pesticide to the moving flow. The dose applied is controlled by matching the application rate of pesticide to the flow rate of the seed. Therefore, it is essential that the flow rate is both known and reasonably stable. The admixture technique requires the use of the appropriate equipment to apply either the dust or spray to the seed. Observations on practical treatments suggest that the above conditions relating to flow rate and equipment are not always met, despite them being a legal requirement under the Control of Pesticides Regulations.

In some cases, it may be appropriate to apply only limited treatments. For example, it may be possible to control surface infestations of mites by treating only the surface layer of seed in a bulk or bin. There are no experimental data to confirm the efficacy of this technique on oilseed rape, although some data exists for use on cereals (Wilkin and Stables, 1985). Experience with cereals suggests that the main limitation of surface treatments may be that, if the lower layers of seed are damp enough to support mites, pesticide applied to the surface will merely cause the mites to move down deeper in the bulk. Therefore, surface admixture should only be used to deal with mites in damp surface layers, where the moisture content of the rest of the bulk is 7.5% or lower.

Some limitations of admixture have been discussed above and more are mentioned in Section 3.9. However, one serious restriction on relying on the admixture of pesticides to control mites in oilseed rape is the occurrence of resistance. Resistance to OP pesticides in some species of storage mites found in cheese stores, was noted by Stables (1985). However, more recently resistance to pirimiphos-methyl has been detected in A. siro from both farm and commercial grain stores (Prickett, 1988; Prickett and Muggleton, 1991). Resistance was detected in 16% of the stocks collected from farms but rose to 71% in mites from commercial stores.The resistance test used is such that any mites surviving the discriminating dose are likely to be resistant to pirimiphos-methyl at a level that would limit the efficacy of practical treatments. The cross resistance of these strains to etrimfos is not known. There is no information available on resistance in mites in oilseed rape stores.

In the only published report to be noted on the use of fungicides for controlling saprophytic fungi in stored rapeseed, rapeseed of 23% and 14% moisture content was treated with 1.5% and 0.75%

propionic acid respectively (Baudet, 1973). Numbers of fungi and bacteria showed large decreases within 5 days of treatment and stayed low for the 35 days duration of the experiment. However, a number of undesirable side-effects, especially the discoloration of the seed rendering it unsuitable for marketing, appeared to preclude its use in practice. This is in contrast to the position with cereals for animal feed where propionic acid has been used successfully as a "preservative" for about twenty years.

3.4 Residues on seed and in oil.

Any chemical applied to the crop during the growing season, during harvest or when it is being stored, may result in residues in the crop that are sufficiently stable to remain up to the point of consumption. Over the past 20 years the dangers associated with applying stable pesticides to crops have become very apparent, and major steps have been taken to ban the use of certain chemicals and to restrict the use of others. However, the fate of a chemical applied at any stage to a crop remains of great interest to regulatory authorities and to manufacturers using this crop.

Data from the Report of the Working Party on Pesticide Residues 1988-89 (Anon., 1990b) indicate that, for cereal grains, residues detected during monitoring were composed entirely of post-harvest pesticides. However, there are some unpublished data to suggest that the crop desiccant, diquat, is detected in samples of harvested grain. The lack of residues of pre-harvest treatments is a reflection of the lack of persistence of the types of chemicals now used and the required interval between treatment and harvest.

There are no data for the routine monitoring of pesticide residues in samples of harvested oilseed rape in the UK or for any other part of the world. All that can be assumed is that, as the spectrum of chemical use is about the same as for cereal crops, most residues will arise from post-harvest treatments. The only exception is that diquat is used more widely on oilseed rape than on cereals, so that the chances of detecting residues of this compound at or after harvest may be higher.

As stated in Section 3.3, a large proportion of the UK crop may be treated with one of two organophosphorus pesticides during storage. Unlike many pre-harvest treatments, there is no withholding period for post-harvest treatments, so that it is difficult to predict the likely level of residues at the time of processing. Work by White and Nowicki (1986) and Good et al. (1977) indicate that the organophosphorus pesticides etrimfos, malathion and pirimiphos-methyl were stable during storage of treated seed. With both groups of workers, the residues detected at the end of storage trials were not significantly different from those at the start.

Limited information is available on the effects of crushing and

oil extraction on residues of pesticides. The commercial oil extraction process consists of a mechanical crushing, followed by a hot solvent extraction. The oil is then refined by various processes, including bleaching and steam distillation. The extraction process mimics that used to extract pesticide residues for analysis, so it is not surprising that in laboratory trials all the residue in the seed was found in the oil and virtually none detected in the expeller (Good et al., 1977; Stables et al., 1979; Chamberlain,1981). The level of residue detected in the oil varied with different pesticides: with dichlorvos and etrimfos, almost no residues were found in the refined oil (Anon., 1975a; Chamberlain, 1981); but with pirimiphos-methyl about 30% of the original level on the seed before processing was detected in the refined oil (Good et al., 1977).

There are no reports of work being carried out at a commercial scale to collect data to support the laboratory trials reported above. However, the limited information that is available indicates that the regime of post-harvest treatments currently used in this country are likely to result in some pesticide residues in oil used for human consumption. However, it is likely that the levels will not be greatly different to those currently found in cereal grains and cereal products. They will contribute to the total daily intake of pesticides and, therefore, there is an urgent need to obtain more accurate information about the actual levels of residue and their frequency of occurrence.

3.5 Rodents

There is no published information available for the control of rodents on stored rapeseed but data on rodents in cereals probably apply.

Rodent proofing of buildings is the preferred, long-term solution to rodent infestation (ANON, 1982).This should be carried out immediately after other control action has been taken.

The most efficient method of controlling existing rat populations is by poison baiting using one of the anticoagulant poisons. The so called "first generation" anticoagulants, warfarin, coumatetralyl, chlorophacinone and diphacinone are effective against rats over most of the UK. These are all available either already formulated in bait or in concentrates. In certain areas rats are resistant to warfarin. These include a large area on the Welsh/English border incorporating Powys and Shropshire, parts of central southern England and an area between Glasgow and Edinburgh (MacNicoll and Gill, 1987). In these areas the "second generation" anticoagulants,difencoum, bromadiolone or brodifacoum should be effective, although the latter is only registered for use indoors by professional pest control operators. In those areas of central southern England where rats resistant to difenacoum are present (Redfern and Gill, 1978), the non-anticoagulant poisons calciferol or zinc phosphide should be

used. Resistance to both first (Rowe and Redfern, 1965) and second generation anticoagulants (Rowe et al., 1981) is widespread amongst house mouse populations and the non-anticoagulant calciferol is the recommended poison (Rowe et al., 1974), although this is often supplied in a formulation that also contains warfarin.

Rodent bait formulations are cereal based and clearly such material must be kept free from insects and mites in order to avoid contamination of stored rapeseed.

Wild rats and wild house mice have highly developed neophobic responses to novel objects and, in particular, novel food (Barnett, 1958; Kronenburger and Medioni, 1985). This trait enhances the ability of animals which consume a sub-lethal dose of poison to subsequently associate the onset of poisoning symptoms with the novel food. They thus develop a learned or "conditioned" aversion to the bait (Robbins, 1980) and become very difficult to control using that particular bait formulation. This is particularly important with acute poisons such as zinc phosphide.

A variety of factors may influence treatment outcome. The presence of animals that are physiologically resistant to first generation anticoagulants will prolong the length of treatments (Rennison, 1977). Not all control problems, however, are attributable to resistance. A failure to lay sufficient baits in the appropriate places may interact with the social organisation of the rodent population to yield poor results (Fenn and Macdonald, 1987; Shepherd and Inglis, 1987). In some circumstances treatment of too small an area may lead to rapid reinvasion of the problem area from surrounding reservoir populations (Rowe et al., 1987). The length of treatments is positively correlated with population size (Greaves et al., 1988). This may in turn reflect the quality and/or abundance of the alternative food supply and, hence, the relative attractiveness of the bait. Almost by definition rodents living in or around stored products have an abundant alternative food supply and it would thus not be surprising if poison bait treatments were less successful in these environments than on premises where stored products are absent.

Should treatments fail because of poor bait acceptance and leave a residual rodent population, then either contact poisons or trapping may be appropriate.

3.6. Fumigation

For many years one course of action followed when an infestation of insects was discovered in bulk stored grain or seed crops such as rapeseed during trading was to recommend a fumigation.

Fumigation can also be effective against mites and fungi, although the amount of experimental data on control of the former is small compared to insects, and with the latter the dose required would be unacceptably high.

The number of fumigants available for use on harvested crops or foodstuffs has been reduced in recent years because of concern over residues and long-term toxic effects. Formerly, a liquid fumigant mixture of carbon tetrachloride and ethylene dichloride was often recommended to treat infestations in bulk grain (Bell and Rowlands, 1983). This worked reasonably well because the liquid application resulted in gas being distributed to all points and the heavy vapours diffused away slowly. Today only methyl bromide and phosphine have widespread approval. However, methyl bromide cannot be used on bulk commodities without some means of forced circulation, while with phosphine the problem is in retaining gas for an adequate period because of its excellent powers of diffusion. In this case the gas is produced from aluminium phosphide -based powder or tablets which, on contact with atmospheric moisture, release phosphine over a 1-3 day period, depending on the temperature and relative humidity. Gas concentrations tend to require such a long time to build up in the deeper levels of a large grain bulk that there is an insufficient exposure time at these points for kill of the pests present. There are a serious lack of data but movement of gas through bulk rapeseed is likely to be slower than through grain because interstitial spaces are much smaller.

A further problem for large bulks is that there is no method of treating only part of the bulk when infestation is restricted. Other difficulties arise because of the need to deal with infestations at temperatures below 10°C when exposure times need to be extended beyond 16 days for control to be achieved.

For smaller storages the principal problem is one of sealing, as these stores suffer proportionately greater gas loss problems than larger ones because of their surface area to volume ratio. For every halving of bulk size, the rate of loss of gas per unit volume is increased by over one and a quarter times (Bell et al., 1991).

3.7. Modified atmospheres

Controlled or modified atmospheres are now used by the agricultural and food industries in a number of countries for disinfesting, preserving and protecting crops from harvest right through to the packaging of finished products. In the UK most usage has been confined to fruit storage and to the packaging industry, but recently there has been more interest in use of the method to control pests in cereal grains.

The principle of modified atmosphere storage is to raise the

level of carbon dioxide to 40% or more and/or reduce the level of oxygen to less than 2%. This modified atmosphere must be maintained for a period of days, depending on the temperature of the commodity and the pests to be controlled, so some means of containing the atmosphere is required. The degree of sealing can vary as leakage can be compensated for by a constant bleed of fresh low oxygen/high carbon dioxide gas. However, in practice bin-type storage is usually considered to be most suitable for controlled atmosphere storage.

Methods currently available for the provision of suitable atmospheres include the supply of gas from transported cylinders and cryogenic tanks, carbon filter- or membrane-based molecular sieves, catalytic converters, exothermic generators and biogeneration systems. The current widespread concern about residues of chemicals and pesticides in foodstuffs could lead to a large increase in the use of carbon dioxide or nitrogen-based atmospheres, as they are known to be able to control pests and delay fungal spoilage in a residue-free treatment system (Jay and Pearman, 1973; Shejbal et al., 1973; Storey, 1973; 1980; Navarro et al., 1979; Banks, 1979; Banks et al., 1980; Jay, 1980; Jay and D'Orazio, 1984; McGaughey and Akins, 1989). However, there are only limited data available on the use of these methods for controlling either mites or micro-organisms, and little work has been done on the suitability of modified atmospheres to control infestation in oilseed rape. Armitage (1980) showed how storage of dry rapeseed (8% mc) in an airtight bin prevented surface moisture uptake by surface seeds in the winter and, although it lowered mite numbers at the surface, it did not greatly reduce overall peak numbers. Poisson et al. (1980) showed how mould growth accelerated in seed at 12, 15 and 18% mc but did not change in airtight-stored seed. The fat acidity increase was attributed to micro-organisms, as sterilised seeds showed no increase in acidity. They mentioned the formation of off-odours in high moisture seed stored at high temperatures, but claimed that these had no repercussions for oil quality.

Limited experimental work in the UK has shown that either the exhaust from an exothermic burner or carbon dioxide can be used to control insects in bulk cereals (Bell et al., 1990; Bell, 1987). However, the cost-effectiveness of the technique is directly related to the quality of sealing of the storage environment that can be attained. The current lack of commercial availability of suitable burners and systems to store and dispense carbon dioxide must also inhibit the use of controlled atmosphere storage. Further restrictions are placed on the use of the method by lack of clear guidance on its status under the Control of Pesticides Regulations.

3.8. Physical control

The development of mites and micro-organisms depends on equilibrium relative humidity (erh) and temperature, and manipulation of these factors can be used as a control measure. In practice, mites rarely develop below 65% rh and fungi below 70% rh. Drying and cooling are covered in detail in Part I of this review. However, it is appropriate to discuss the biological consequences of drying and cooling and the part that they play in an integrated approach to storage. Different types of grain have different erhs, dependent largely on the chemical composition of the seed, especially its oil content. Oilseed rape contains about 45% of oil and has an equilibrium mc at 70% rh and 25°C of 7-8% mc depending on variety, compared to 14-15% mc for cereal grains that contain only 2% of oil.

The overall chemical composition of a seed also affects its mc/erh relationship and different varieties of a species can have different relationships. This aspect is discussed in section 4.3. Although the mc in equilibrium with 70% rh is frequently quoted as "safe" for storage, it has already been pointed out that mites can develop at 65% rh. Mites are common pests in oilseed rape so it is recommended that, for safe storage, the mc be reduced to a level in equilibrium with 65% rh or below. However, it is very difficult to use this figure to quote a single, safe storage moisture content as this will vary according to the temperature of the seed. This mc will also differ slightly depending on whether the seed is adsorbing or desorbing moisture, the value being greater for adsorption. Although seed put into store is likely to have been dried, it is hygroscopic and will thus readily adsorb moisture at the surface of a bulk in humid conditions. It is therefore prudent to consider the adsorption relationship when predicting a safe storage mc. Henderson and Wilkin (1985) presented a mean mc/erh relationship for three varieties of double low oilseed rape, adsorbing moisture at 25°C (Fig. 1) but also determined it at 5°C and 15°C. The equilibrium mc at 70% rh was found to be 8.5, 8.3 or 8.0% at 5, 15 and 25°C, respectively, compared to 7.7, 7.5 or 7.3%, respectively at 65% rh. These figures suggest that a mc of 8%, often accepted as safe, may be too high, particularly shortly after harvest when temperatures are likely to be high. From the economic point of view, recommending a safe storage mc of 7-7.5% may not be very attractive to a farmer (Wilkin *et al.*, 1987). The current commercial trading standard is 9% and reducing seed to nearly 2% below this may cost a farmer £6 per tonne in weight loss and drying costs. However, as the oil content of seed is measured on a wet weight basis, reducing the mc increases the percentage oil content. The farmer is paid a bonus according to oil content and therefore will recoup about a third of the value of the weight losses caused by drying. This may help to justify storage at 7.5% mc and will bring the additional benefit of a reduced dependence on pesticides.

Practical trials in England with seed stored at 8% and 9% mc confirmed the belief that large populations of mites could develop under these conditions (Armitage, 1980). However, the work also demonstrated that the appropriate use of aeration could lead to a marked reduction in mite numbers.

It is essential to measure mc of the seed as accurately as possible, in order to make predictions about safe storage. Henderson and Wilkin (1985) used the BS 4289, Part 3 (1987) oven drying method. The use of other methods, or of moisture meters that have been calibrated using other methods or have been poorly maintained, could produce misleading results. It is also worth noting that Henderson and Wilkin (1987) found that moisture results on oilseed rape determined by BS4289 varied by up to 0.7% mc, when sub-samples from a well mixed bulk were tested at different laboratories.

Mites are susceptible to mechanical damage and Pierre (1974) showed how mite numbers fall after moving the seed and claimed the practise was valuable in the short term. In view of the damage caused to the seed during conveying and the temporary nature of the effect on mite numbers, there does not seem to be great merit in the process, except as a means of disinfestation immediately prior to sale.

3.9 New developments

In many respects the prospects for new approaches to pest control during storage seem remote. Oilseed rape is a minority crop in the U.K. and it seems unlikely that current markets for the oil or expeller will allow a considerable increase in levels of production without a serious risk of creating surpluses. Given the present approach to funding agricultural research, it is difficult to imagine major research on storage projects being funded by central government resources.

The development of new chemical control agents is generally funded, at least in the early stages, by the pesticide manufacturers. However, the market for post harvest use of pesticides on oilseeds is very small and appears to be restricted to the U.K. It should be noted that not all the pesticides cleared for admixture to cereals here, are also approved for use on stored oilseed rape. This is, presumably, because the manufacturer has decided that the costs of approval are not justified on the basis of projected sales. Therefore, it seems very unlikely that a pesticide manufacturer is going to invest in the development of a new post-harvest pesticide for oilseed rape. It is also unlikely that new pesticides developed for the cereals market will be approved for use on oilseeds.

In addition, continued use of existing pesticides may be in jeopardy. There are suggestions from the EC that Maximum Residue Limits (MRLs) for pesticides on oilseed rape, should be introduced. The proposed levels would be less than one quarter of the current U.K. application rates and so would, almost certainly, preclude their continued effective use. Pesticide use on stored oilseed rape in other EC countries seems to be almost non-existent, so it is likely that the proposal will cause minimal disruption to member states, other than the U.K.

Some new developments in fumigation techniques for cereal grains, such as the use of bag blankets (Reichmuth et al., 1985) or the use of cylinder based supplies of phosphine (Winks, 1990; Bell et al.,1990a) have been reported recently. These developments may well bring advantages of increased efficacy and reduced costs but some research and development on oilseeds is needed before results obtained from treating cereals can be extrapolated to oilseed rape.

Work on an integrated storage strategy for cereal grains (H-GCA Project Report No. 24, 1990) has shown the potential for greater use to be made of physical control methods. It is possible that this approach could be applied to oilseed rape but much research is needed before a practical strategy can be proposed. However, the likely restrictions on pesticide usage mean that the importance of developments in this area may become much more necessary in future.

Biological control of storage pests is being investigated in some countries, with particular reference to cereals. Mites can be controlled by predatory mites, notably of the genus Cheyletus. Norris (1958) showed that populations of A. siro reduced as numbers of Cheyletus eruditus rose. Other workers, notably Pulpan and Verner (1965), have reported that infestations of pest mites in grain can be controlled by adding predators and some methods for breeding and handling the predators have been developed. Whilst there are no data relating directly to the control of mites in oilseed rape using predators, there are no reasons why the technique should be any less successful than when applied to cereal grains. Unfortunately, there are two practical considerations that are likely to seriously limit the application of biological control of mites infesting oilseed rape stored in the U.K. Firstly, mite infestations in oilseed rape often occur in seed at temperatures below 15°C and, under these conditions, predation is unlikely to be sufficient to limit pest populations. Secondly, there is currently no commercial supply of predators and it seems unlikely that one will be forthcoming for such a limited use as oilseed rape.

As reported in Section 3.7, controlled or modified atmosphere storage may have some potential for controlling pests and limiting fungal growth in the future. However, its adoption is totally dependent on the availability of suitable equipment and the granting of Approval by the regulatory authorities. It must also be borne in mind that the technique cannot be applied to many types of storage, so that controlled atmosphere storage will not provide a complete answer to all storage problems.

The main conclusion that can be drawn from the above, is that the options for new control measures to deal with storage problems are very limited. A key reason for the very small number of new options, and also for the limited data on the efficacy and application of existing methods, must be the lack of a cohesive programme of research. Fortunately for the producers of oilseed and the users of oil and expeller, there are few proven links between storage problems and the health of people or animals consuming these materials. However, current research on food allergies and new methods of detecting a range of food contaminants including fungal biomass and mycotoxins, could result in a marked change in attitude towards problems that occur during storage.

4. PROBLEMS ASSOCIATED WITH NEW VARIETIES

4.1 Introduction

The breeding of a new variety of plant is usually undertaken with clearly defined aims. However, even if these are achieved, it is possible that other, unplanned and unforeseen changes, will be induced. Unfortunately, these changes may be so far removed from the aims of the plant breeders that they may go unnoticed until after the new variety has been commercialised.

In addition, some changes that are highly desirable may also have secondary effects that are less acceptable. A good example of this is the removal of glucosinolates and erucic acid from oilseed rape. These chemicals, which occur in both the growing plant and the seed, are linked to human and animal disease. The development of varieties of oilseed rape producing seed with only very low levels of these chemicals, has been a goal of plant breeders for some time. The removal of these chemicals will extend the potential use of the oilseed expeller in animal feed and reduce the potential risk of using the oil as a human food. However, these naturally occurring chemicals were probably evolved by the plant as part of a defence mechanism against attack by grazing animals and insect pests. It is almost inevitable that their removal will also affect the susceptibility of the plant and seed to pest attack. There may, of course be other changes associated with the new varieties that could influence the storage of the seed which, as yet, have not been investigated. These could include susceptibility to fungi and changes to moisture content/equilibrium relative humidity relationships.

4.2 Pest resistance

The varieties of oilseed rape currently grown in the U.K. are undergoing a phase of rapid change. These changes could have fundamental effects on the storage properties of seed. In particular, new varieties being developed could have much lower resistance to pest attack, both in the field and during storage.

Oilseed rape is always grown as part of an arable rotation so that it is very likely to be stored on farms in conjunction with cereal crops. The same pattern of storage often applies in commercial stores, with only limited segregation between bulks of oilseed rape and other grains. Therefore, the risk of cross infestation by insect pests between stored wheat or barley and oilseed rape must have existed for many years. The lack of past records of such infestations developing has always been put down to the inability of the insects to develop on what was considered as an unsuitable food. This was confirmed by the results from infestability trials, at least with some varieties, reported in Section 2.3. However, the same work also indicated that some species of stored grain insects could complete their life-cycle on one or two varieties of oilseed rape that contained only low

levels of glucosinolates and erucic acid. Recent observations by MAFF regional advisers have shown that for the first time, storage insects have been found infesting oilseed rape in both farm and commercial stores.

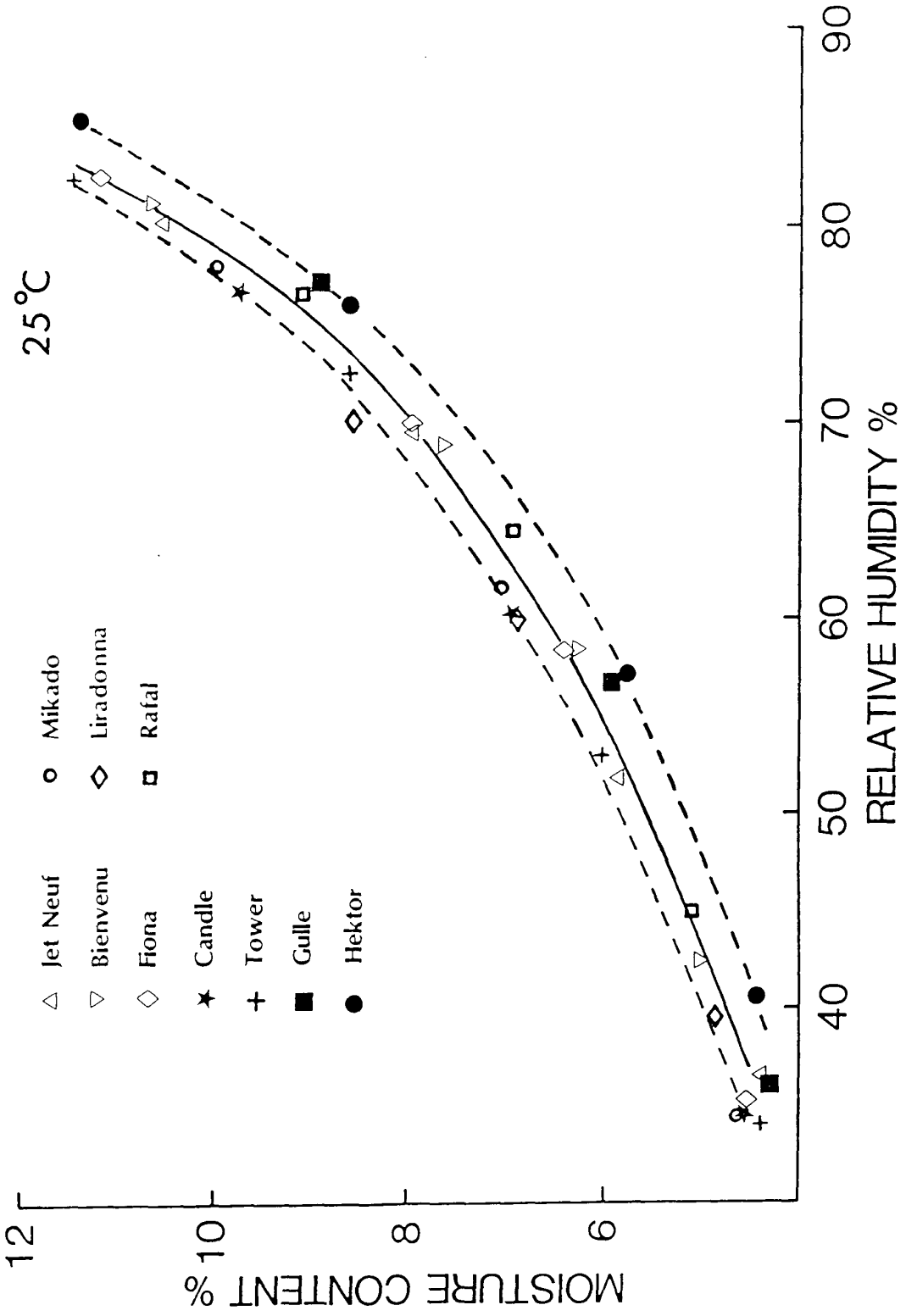
As yet, there are insufficient data to allow the risk of infestation by storage insects to be assessed. However, it seems likely that if some new varieties are susceptible to infestation by the common insect pests, then a new series of control problems will have to be solved. These would be additional to the existing problems of mites and fungi.

4.3 Moisture content and related problems.

This topic is dealt with in more detail in Part I of this Review. The composition of oilseed rape, perhaps more than any other stored product, has continually changed during the last decade, particularly as varieties with low glucosinolate and erucic acid content have been developed. Varietal differences have affected the mc/erh relationship. Pixton and Warburton (1977; 1981) determined mc/erh relationships for different varieties of oilseed rape, including Candle and Tower, two of the earliest "double low" varieties, and some older varieties with high levels of these compounds. Henderson and Wilkin (1985) and Wilkin et al. (1987) determined the relationship for some of the more recent "double low" varieties and compared results of these with earlier varieties (Fig. I). Variety made a difference of nearly 1% mc to the safe storage mc of oilseed rape, the "double low" varieties having the higher safe mc's. The results plotted in Fig.I were determined at 25°C but reducing the temperature by 20°C permits the mc to be increased by about 0.5% (Pixton and Warburton, 1977). The varietal differences observed suggest that there is a need to determine the mc/erh relationship of new varieties of oilseed rape in order to give the best possible predictions on safe storage.

In order to assess the storage potential of oilseed rape, it is essential to measure its mc as accurately as possible. For maximum accuracy, moisture meters must be calibrated regularly, if possible, using the variety most likely to be tested and grown in the current season. There is evidence that moisture results obtained with electrical meters vary according to the variety. Stenning and Channa (1987), using a conductance-based moisture meter, found a varietal difference of 1.4% mc with oilseed rape in the important central part of the moisture range. They also found that the oil content of oilseed rape had a significant influence on the results of the same meter; in the order of -0.3% mc for every +1% change in oil content. Henderson (unpublished) using cereal grains found not only a varietal but also a seasonal difference of about 1%. There is, therefore, clearly a need to check the calibration of moisture meters each season using new varieties as they are produced.

Figure I. The relationship between moisture content and equilibrium relative humidity for different oilseed rape varieties, over a practical range of moisture content, adsorbing at 25°C. The solid line is the mean of Jet Neuf, Bienvenu and Fiona varieties, and the broken lines are for Candle and Hektor.



There is no evidence to suggest that results of oven-drying methods for determining mc are affected by varietal differences in oilseed rape although such differences have been demonstrated in cereals (Oxley et al., 1960).

4.4 Conclusions

Changes in the chemical composition of oilseed rape, brought about by the development of new varieties, can have fundamental effects on the storage properties of the seed. However, these effects are not considered by current breeding programmes. Therefore, any storage problems associated with a new variety will not come to light until a very late stage of development or even after full commercialisation.

This point should be recognised by future plant breeding programmes and assessments of storage potential should be included at an early stage of development. A further requirement is that there should be closer liaison between plant breeders and researchers in the fields of crop husbandry and storage biology.

5. GENERAL CONCLUSIONS AND RECOMMENDATIONS

In comparison with cereal grains the fundamental features of the storage of oilseed rape are poorly researched, especially when taking account of U.K. conditions of production, storage and marketing. A very large part of the more basic research comes from overseas sources, notably Canada, whereas data from the U.K. are often in the form of limited investigations, ad hoc work or casual observation.

Despite these limitations a good pool of background information exists on the biology and ecology of the major pests: mites and moulds. This is, almost without exception, derived from work on cereals and there is only limited information on the physical characteristics of stored oilseed rape, so that it is currently impossible to exploit fully biological knowledge of pests in control programmes.

Lack of data on the relationship between moisture content, temperature and the resultant equilibrium relative humidity, is the principal constraint on developing more precise storage recommendations. This situation is not helped by the current U.K. trading standard for moisture of 9% and the lack of information on reliability of methods of moisture measurement. In particular, there would be value in examining the possibility of producing a method of moisture measurement that was unaffected by the lipid content of the seed.

There has been no comprehensive survey of oilseed storage in the U.K., so detailed information on the frequency and severity of problems is lacking, as are data on the relationship between problems and storage practice. Indications are that problems associated with the development of mites and fungi, do occur both at a farm and commercial storage level. On occasions these problems give rise to serious financial loss. There are some indications that problems caused by infestations of storage insects are becoming more common. Limited laboratory data suggest that this may be a consequence of the change to double low varieties of seed, although not all double low varieties are equally susceptible to insect attack.

Laboratory data generated more than 10 years ago, and other information from cereal research, have provided a good basis for the development of chemical control by admixing a pesticide with the seed at the start of storage. Ministry of Agriculture, Fisheries and Food (MAFF) pesticide usage survey data show that such chemical control is very widely used, with 60% of the crop being treated. This high level of use hopefully reflects the efficacy of these treatments, although once again there are a lack of supporting field data. However, such a high level of pesticide usage must also be an indicator of the frequency of potential storage problems which, in turn, is a consequence of the trading standard for moisture. MAFF data indicate that

fumigation is used on occasions to disinfest oilseed rape during storage, but there is a total lack of data as to the specification for such treatments, their efficacy, or the consequences in terms of residues in the seed, oil or expeller. Indeed, the overall lack of information about levels of chemical residue in the seed at the time of harvest and the fate of residues in the processed crop is a serious gap in the data on pesticides in the diet of humans and animals.

Storage practices in the U.K. may have to change in the near future if proposed EC legislation on pesticide usage is implemented. This could set Maximum Residue Limits (MRLs) for oilseed rape that would be about one fifth of current application rates and would, almost certainly, preclude the continued use of admixture of a pesticide to control mites. The only practical alternatives, applicable to the majority of the crop, would appear to be fumigation and/or drying to a lower moisture content than is the current norm. The lack of data on fumigation has already been mentioned, as have the lack of precision in predicting and measuring safe storage moisture contents. A better understanding of the moisture content/equilibrium relative humidity relationships of oilseed rape, coupled with data on pest biology and seed cooling, would allow storage strategies to be developed that minimised extra drying without risk of mites or fungi. As it is, the only safe recommendation that can be made is to dry seed to 7% moisture content. Unfortunately, this advice would seriously disadvantage U.K. producers in relation to producers in other European countries, where drier conditions prevail at harvest. In the longer term, it may be possible to exploit bio-technological developments to endow oilseed rape with properties that will reduce its susceptibility to infestation during storage. However, there seems little potential for such solutions this century.

The overall conclusion is that the amount of research on the storage of oilseed rape, particularly that aimed directly at U.K. problems, is inadequate in relation to the value of the crop and its end use as a human food. Current storage practice is based on a simplistic knowledge of safe moisture contents and a heavy reliance on pesticides based on data extrapolated from cereal storage. The former is not cost effective and the latter may become inappropriate because of legislation or the development of resistance. It seems unlikely that quality standards for seed will diminish, so that pressures on producers and storers of seed to deliver a high quality product to the market, free from pests or moulds, will continue or even increase.

In the light of these conclusions the following specific recommendations for future research can be made:-

1. Collection of information.

It is recommended that an information gathering exercise is undertaken covering farm and commercial stores holding stocks of oilseed rape. This exercise would collect information on current harvesting, drying and storage practices, as well as ascertaining details of insects, mites, fungi and mycotoxins present in the seed after 3 months storage.

2. Storage properties of new varieties

Liaison links should be established between plant breeders and storage scientists to set up a programme to assess the storage properties of new varieties of oilseed rape with commercial potential.

3. Moisture content/equilibrium relative humidity relationships

The moisture content/equilibrium relative humidity relationships of a selection of new, double-low varieties of oilseed rape should be determined. This information should then be used to provide more precise recommendations on safe storage conditions. An investigation should be undertaken to produce a water-specific method of measuring moisture content in oilseed rape.

4. Infestability of new varieties

Work should be undertaken to explore in more detail the changes in infestability by insects and mites that may have accompanied the changes in chemical composition associated with new, double-low varieties.

5. Use of fumigants

Limited work should be undertaken to investigate the efficacy of fumigation of oilseed rape with phosphine and of any effects on the seed, oil or expeller of such fumigations.

6. Assessment of chemical residues

A study should be undertaken to determine the levels of pesticide residues currently occurring in oilseed rape at the time of processing. Depending on the results of this study, further work may be needed to investigate the fate of residues during processing.

7. Storage strategy

Given data arising from some of the above proposals, it is recommended that efforts are made to develop an integrated storage strategy for oilseed rape. This strategy would be similar in approach to the one developed for cereals and would allow pesticide use to be reduced to a level at which it would conform to the proposed EC legislation. The strategy would also aim to reduce storage costs.

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