Chapter 2 –
Moisture Migration and Surface Ventilation

This chapter explains how and why moisture migration takes place and discusses to what extent surface ventilation can reduce or eliminate the damage it can cause to bulk grain cargoes.

2.1 Movement of Moisture

During the voyage it is usual for moisture migration to take place. Part of the moisture migrates to be either lost to the external atmosphere as a result of ventilation, or drained off into the bilges. However, in some cases the total amount of water held in a cargo may be the same at the end of a voyage as it was at the beginning but, as a result of moisture migration, the moisture content of some parts of the cargo may have changed considerably.

In countries such as India and China, grains and other agricultural products might come from a number of locations and so may have different moisture levels. It can be very difficult to obtain a representative sample to determine the correct pre-shipment moisture or to ascertain whether the moisture level is below the threshold that can trigger condensation or 'sweat'.

In addition, grain cargo is often laid into open spaces for drying before it is moved to assembling places, which means that some lots will have higher moisture content than others.

2.2 Physical Considerations

2.2.1 Vapour Pressure (VP) and Relative Humidity (RH)

Vapour pressure (VP)
The earth's atmosphere is a mixture of 78% nitrogen, 20.9% oxygen and approximately 1% of other gases, including water in the form of vapour. Pressure exerted by the atmosphere will partly depend on the pressure exerted by the water in vapour form, and this proportion of the total atmospheric pressure is known as the 'water vapour pressure' of the air at that time.

Saturation vapour pressure (SVP)
As the quantity of water in the atmosphere increases, the VP will increase proportionately. At a given temperature, the air can only hold a specific amount of water vapour and the pressure exerted in the atmosphere when this limiting point is reached is referred to as the 'saturation vapour pressure' (SVP) of the air at that particular temperature.

Super saturation
Any attempt to increase the water vapour in the air once it has reached its SVP will produce 'super saturation', where water is deposited from the air in liquid form, either as droplets to form a fog or cloud or in the form of water drops on suitable surfaces, eg as sweat in a ship's hold.

Relative humidity (RH)
Under most circumstances, the VP of water in the atmosphere is less than the SVP. The percentage value of the actual VP in relation to the SVP is defined as the 'relative humidity' (RH) of the atmosphere. Therefore, if the air only holds half its potential maximum amount of water in the form of vapour, the relative humidity will be 50%. At SVP, the relative humidity will be 100%. Warm air is capable of holding more water vapour than cool air, so the actual weight of water that is required for saturation increases with increasing temperature. Therefore, for a given volume of air containing a constant weight of water vapour, the RH will vary as the SVP changes with the temperature. If the temperature rises, the SVP will increase and the RH will fall.

If the temperature rises and the water vapour is constant, relative humidity falls.

Relationship at different temperatures
Figure 2.1 shows the relationship between VP and RH at different temperatures, eg 100% relative humidity at 10°C represents a water vapour pressure of 9.2 mm Hg and at 30°C of 32 mm Hg, ie an increase of 20°C has resulted in more than a three-fold increase in the water-holding capacity of the atmosphere.

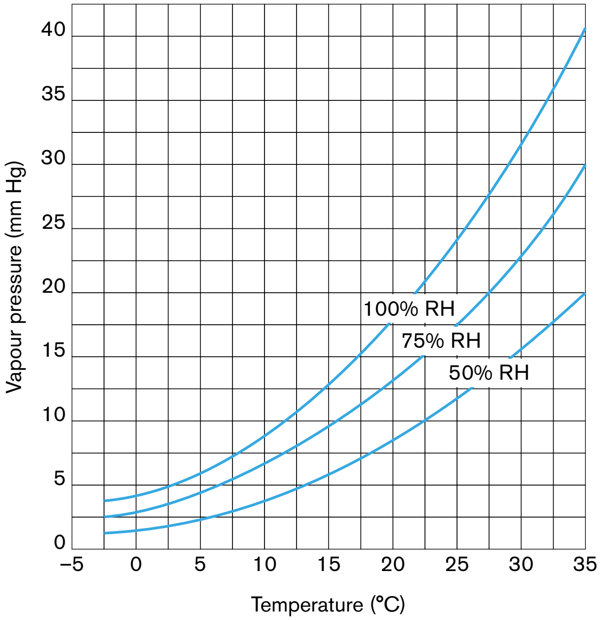


Figure 2.1: Relationship between vapour pressure and relative humidity at different temperatures.

Condensation

If air is cooled to the point where saturation (100% RH) is reached, moisture will begin to be deposited in the form of droplets or mist (ie condensation will occur).

Ship's sweat

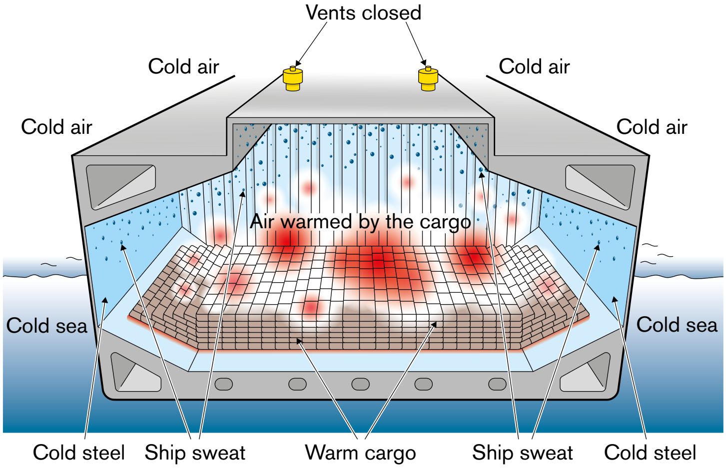


Figure 2.2: Warm cargo in a cold atmosphere resulting in ship's sweat.

If the air in a ship's hold is warm and it comes in contact with the deckhead, which has become cooled by the outside atmosphere, condensation will usually form on the deckhead in the form of sweat.

2.2.2 Equilibrium Relative Humidity (ERH) (Water Activity)

All biological materials normally contain a certain amount of water. The amount of moisture present at any given time is termed the moisture content. If the material comes into contact with dry air, it will tend to lose a small proportion of its water to the air in the form of water vapour. This process will continue until there is an 'equilibrium' of the air in contact with the material of that particular moisture content and at that particular temperature. Equilibrium relative humidity (ERH) is sometimes referred to as 'water activity' and it is measured as a ratio rather than as a percentage, so an equilibrium relative humidity of 50% is equivalent to a water activity of 0.5.

In bulk grain cargoes, where air movement within the bulk is very restricted, the moisture content of the atmosphere within the cargo (which is also termed the 'interstitial' or 'inter-particular' air) is, under normal conditions, completely controlled by the temperature and moisture content of the cargo.

Experimental work with maize has made it possible to construct graphs that equate ERH with moisture content at various temperatures. Such graphs are known as 'desorption isotherms', since all the experiments were constructed so that, to achieve ERH, moisture was given up by the maize to the surrounding air. If the air around the maize is wetter than the ERH, the maize will absorb moisture from the air. Such a process is known as 'adsorption' and a similar series of curves or isotherms may be constructed, called 'adsorption isotherms'. The relationship between adsorption and desorption isotherms is a complex one, but it may be stated that, under conditions of desorption, the ERH at any given moisture content is slightly lower than under conditions of adsorption.

Normally in the grain trade, from harvesting through to the discharge of cargo, there is a tendency for the grain to lose moisture to the surrounding atmosphere.

2.3 Moisture Migration

Moisture migration can be expressed as follows:

Change of temperature → change of ERH → change of vapour pressure

The mechanism by which moisture migration operates can be illustrated by considering an example cargo of bulk maize, a commodity where migration is generally slow.

The interstitial air, which occupies some 40% of the cargo space in the case of bulk maize, will contain water vapour. The VP in this air will rapidly reach equilibrium with the moisture content of the maize. In maize with a moisture content of 14% and a temperature of 25°C, the RH of the interstitial air will rapidly reach 68% and the water vapour pressure in the air at that time will be 16.3 mm Hg. A change in the temperature of the maize will result in a change of the ERH and in the VP. Table 2.1 shows equilibrium temperatures for maize at 14% moisture content. The temperatures at which SVP occurs (ie 100% relative humidity) are included in the table, and these temperatures are known as the 'dew points'.

Temp (°C)	Equilibrium RH (%)	Vapour pressure (mm Hg)	Dew point (°C)
15	60.0	7.1	7.4
20	64.4	11.2	13.0
25	68.0	16.3	18.7
30	71.5	22.9	24.3
35	75.0	31.5	30.0

Table 2.1: Temp/ERH/VP/DP – Relationship of maize at 14% moisture content.

Table 2.1 shows that air at 25°C and 68% ERH will have a VP of 16.3 mm Hg. If this air is reduced to a temperature of 18.7°C, moisture will be deposited because the SVP will have been reached. If a ship carrying maize of 14% moisture content with a temperature of 25°C passes into a region of colder water, the outside of the cargo will assume the temperature of the cold sides of the vessel. If we assume this to be 15°C, it can be seen that the maize will have an ERH of 60% and a VP of 7.1 mm Hg.

The cooling process of the colder sea will not noticeably affect the maize in the centre of the bulk, since maize is a poor conductor of heat. Therefore, the maize in the centre of the stow will still have a temperature of 25°C and the interstitial air in this region will still have a VP of 16.3 mm Hg.

A VP difference is created between the interstitial air in the maize in the centre and the interstitial air in the maize on the periphery of the stow.

Consequently, there will be a flow of moisture vapour from the high pressure region to the low pressure region in order to equalise the pressure difference, so water will move from the centre towards the periphery.

This movement of water from the inner portion of the cargo will have the immediate effect of causing a reduction in the VP of the air there, but equilibrium conditions will be restored as a result of more water moving from the grain into the interstitial air, so the original VP of 16.3 mm Hg will be maintained. Consequently, there will be a continuous flow of water vapour from the warmer part of the stow to the colder part.

The isotherm graph in Figure 2.3 shows ERH plotted against moisture content.

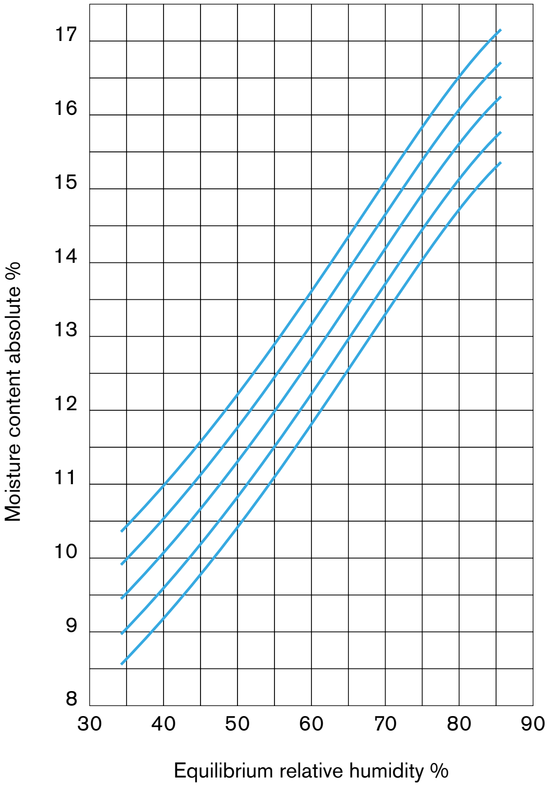


Figure 2.3: ERH plotted against moisture content.

Cargo sweat at periphery

In the example, the overall effect of this transfer of moisture vapour will be to cause deposition of physical water in the periphery of the stow that is in contact with the cold hull. This follows from Table 2.1, which shows that a VP of 16.3 mm Hg at 25°C will have a dew point of 18.7°C. As this dew point is higher than the temperature of the cargo at the periphery, water will be deposited on the cargo and cargo sweat will be produced.

This example is an oversimplification of what happens in practice, as there is a tendency to set up a temperature gradient in the maize, along the route from the inside of the stow to the outside, and there will be a gradual drop in the temperature of the air that moves and the grain in contact with it. As water vapour will be absorbed en route, lowering the dew point of the air moving towards the periphery of the stow, it is not possible to make an exact prediction of the conditions that are necessary for cargo sweat to occur.

Heating up

If there is a temperature differential between the outside of the stow and the inside, moisture migration will result from the mechanism described. Such moisture migration will also occur when one part of the bulk heats up for any reason, eg insect infestation, microbiological activity or proximity to a hot bulkhead. In all these circumstances, moisture will migrate from the warmer region to colder parts of the stow.

Monitoring the cargo temperature on board, when it is safe to do so, can also provide valuable information regarding whether the cargo is self-heating. With some cargoes, such as soya beans, there will be visible evidence of damage by overheating (as described in Chapter 5).

Warmer to cooler climates

Figure 2.4: Bulk carrier arriving in a colder climate (ice on deck).

The problem of moisture migration is most evident with exports of biological cargo from warmer climates to cooler climates. Moisture migration may occur for many reasons but, irrespective of the cause of the temperature differential, the result will always be (where the moisture content is uniform) a movement of moisture from the warmer to the cooler parts of the cargo.

Moisture migration is observed in cargoes where insect infestation occurs. Here, the respiratory heat from the insects causes centres of heating and moisture migrates from these spots to form a wetter shell in the cooler cargo immediately surrounding the heated zone. As heating becomes progressive, the warmer zone expands and the wetter shell moves outwards.

Another example is where ship's heat causes a localised rise in the temperature of the cargo in contact with the heat source, for example, an uninsulated engine room bulkhead. Here, moisture migrates from the warm cargo and forms a layer of increased moisture content in the cooler cargo adjacent to it.

Unfortunately, the straightforward pattern of moisture movement resulting from a VP differential is not the only phenomenon that results from a temperature differential in a cargo. Where temperature differentials are present, convection currents are set up owing to the fact that warm air is less dense than cold air. Therefore, if heating occurs within a cargo, there will be a tendency for moisture to migrate in all directions from the heating zone. There will also be a tendency for hot air to rise from the heating zone, to be replaced by cooler denser air coming in from the sides and underneath. The warm air will carry more moisture with it, so the pattern of moisture movement will be distorted in a vertical direction.

Where a hot spot occurs in a cargo, moisture movement is greater in a vertical direction than either laterally or downwards because convection currents reinforce the upward movement of moisture.

Therefore, for grain that is loaded warm and subjected to peripheral cooling, the primary moisture movement will be in a vertical direction, so more water will pass towards the top of the cargo than towards the sides. If it is not possible to remove the water migrating to the top region of the cargo by ventilation, more damage may be anticipated in the top layers than at the sides.

2.3.1 The Rate of Moisture Migration

Difference in vapour pressure (VP)

The rate at which moisture moves from a warm to a cold region depends, to a large extent, on the difference in VP between the warmer and colder parts of the cargo. As shown in Table 2.1, the VP of interstitial air of a cargo of maize at 14% moisture content does not increase directly with temperature. As a consequence, an increase in temperature from 15 to 25°C will give a VP increase of 9.2 mm Hg, while a rise in temperature from 25 to 35°C will give a VP increase of 15.2 mm Hg. It therefore follows that moisture migration will be greater, all other things being equal, when moisture is moving from cargo at 35°C to cargo at 25°C than when moisture is moving from cargo at 25°C to cargo at 15°C, although the temperature difference in both cases is the same.

When considering the rate of moisture movement within a cargo, the specific temperatures are as important as the relative difference in temperatures.

Another factor is the differential in temperature in relation to distance, as moisture will move more rapidly from cargo at 25°C to cargo at 15°C if the distances are shorter, because the VP gradient is much greater. In this respect, the thermal conductivity of the cargo will be of considerable importance as the lower the conductivity, the slower any heat will move through the cargo.

Initial moisture content

The initial moisture content is also important. If we consider a cargo of maize at 14% moisture content loaded at 35°C, with its periphery cooled down to 25°C, the equilibrium VPs will be 31.5 mm Hg and 16.3 mm Hg respectively, giving a differential of 15.2 mm Hg. Under the same temperature conditions, but with maize at moisture content of 11%, the equilibrium vapour pressures will be 22.4 mm Hg and 11.6 mm Hg, giving a lower differential of 10.8 mm Hg. In addition (and this is of considerable practical importance), a much greater quantity of water can be absorbed by the cooler grain before the moisture content is raised to a level at which spoilage will commence.

Soya beans are another example where moisture content and temperature are two of the main factors that influence whether the cargo, or part of the cargo, may undergo self-heating (see Chapter 5).

Compactness

Because of the importance of convection currents in moving moisture, the more readily air can move through a cargo, the more rapidly moisture can be carried through.

This means that there will be more rapid moisture movement through a cargo that is less compact (eg pellets) than through a cargo that is powdered, where the movement of air will be very limited.

Relevance to grain

A cargo such as grain, which in this context covers the edible, seed-like fruits of grasses and pulses, has a comparatively low moisture content and the seed itself has a protective outer skin that is relatively impermeable to moisture. Therefore, moisture is released relatively slowly from grain cargoes such as wheat and maize. In addition, whole grain will lose moisture much more slowly than grain that has been milled or pulverised in some way, as the natural protective coating will have been disrupted.

There is little quantitative data for the release of moisture from various products so direct comparisons are difficult. However, in a study of maize, it was found that, in 28 days, a zone of enhanced moisture had moved approximately 1 m in a vertical direction (ie with convection currents reinforcing the moisture movement) from a hot spot. The temperature differential in this experiment was from 40 to 21°C over a distance of approximately 1.25 m. The actual quantities of water involved could not be accurately determined, but there was no doubt that, for many other types of cargo, both the rate of movement and the quantities of water moved would have been many times greater.

When considering the significance of potential moisture migration in a cargo, it is necessary to consider:

- The VP differential in relation to the distance between the hotter and colder zone
- the temperature of the hotter material and the temperature of the colder material to which moisture is migrating
- the initial moisture content
- the nature of the cargo
- the ease with which air may move through it.

Vessels that carry grain in bulk vary in their capability for ventilating the cargo. Considerable quantities of grain are carried in tankers with no ventilation whatsoever. Sometimes grain is carried in vessels fitted with a sophisticated *Cargocaire* system of surface ventilation, which also has facilities for preconditioning the ventilating air. Other vessels have fan-assisted surface ventilation and many others have natural surface ventilation through cowls that is unassisted by any mechanical effort, with the flow of air dependent on the movement of the ship. Some bulk carriers that successfully carry many thousands of tonnes of grain have no means whatsoever of ventilating the surface of the cargo.

However, claimants frequently state that spoilage of grain in transit is a result of unsatisfactory ventilation, or that lack of ventilation has exacerbated damage caused by other factors.

A bulk cargo of grain, if stowed in accordance with the *International Code for the Safe Carriage of Grain in Bulk* (International Grain Code, Reference 3), is not able to be surface ventilated, which suggests that such a cargo is unlikely to be significantly affected by surface ventilation, or from a lack of it. T A Oxley in *The Scientific Principles of Grain Storage* (Reference 4) stated:

"... popular opinion greatly exaggerates the virtues of ventilation … gaseous diffusion and heat movement in grain are both exceedingly slow and, in the absence of mechanical means to force air through bulks, changes in the atmosphere at the surface have a negligible effect on the intergranular atmosphere and on the water content or temperature of the grain."

Figure 2.5: Loading grain.

To reduce moisture movement and its effects within a grain cargo, it would be necessary to reduce the moisture content throughout the cargo or, alternatively, reduce the temperature differential by cooling the bulk of the grain.

A reduction in moisture content and a reduction in temperature could both be achieved by passing significant quantities of air through the cargo. However, through ventilation, while possible in some silos ashore, is not possible on board ship. In practice, only surface ventilation is available to attempt to control the damaging peripheral effects of moisture migration in bulk grain.

2.4 Cargo Sweat

In the case of tankers, while there is general agreement that little can be done about ship's sweat should it occur, it is suggested that, for vessels fitted with natural or mechanical ventilation, the moist air may be continuously removed from the headspace above the cargo to reduce or eliminate condensation occurring on the deckhead. However, it must be remembered that the air used for ventilation is at the same temperature as, or below, the temperature of the deckhead and hatch covers. If the ventilating air is cool, the immediate effect will be to take up moisture vapour by diffusion from the interstitial air in the surface layers of the cargo, because the vapour pressure of the interstitial air will be higher than the vapour pressure of the ventilating air. At the same time, the surface of the cargo will be cooled, both directly by contact with the cooler ventilating air and as a result of evaporation of moisture. The temperature of the surface layer of the cargo may, therefore, be reduced below the dew point of the warm moist air rising from within the bulk. Water will then condense in the cooler surface layers of the cargo, producing a wet cake just below the surface. Microbiological spoilage will eventually occur in this wet cake. Even if no condensation occurs in the surface layer, the moisture content of these layers may rise as a result of absorption of moisture, to a level where microbiological activity can occur, although this damage does not arise strictly from cargo sweat.

If the external ambient conditions are such that ship's sweat would occur in the absence of ventilation, cargo sweat will frequently occur just below the surface if ventilation is employed. This means that, under these circumstances, damage will result whether ventilation is used or not.

Surface ventilation is also claimed to be useful in cooling cargo that is heating, minimising the increase in temperature that might cause further deterioration. It is, however, generally agreed that heat transfer through bulk grain is a very slow process. Work carried out using a vertical heat transfer system with a temperature differential of 20°C indicated that about 32 days' continuous heating was required before there was a rise in temperature of 3°C in maize 1 m from the heat source. So, although microbiological spoilage produces serious heating, surface ventilation cannot significantly affect a heating process that is occurring more than about 1 m below the surface.

Figure 2.6: Surface damage to cargo as a result of ship's sweat.

What can occur when the surface of a heating cargo is continuously cooled by ventilation is that the VP differential between the interior of the cargo and the periphery is maintained and, consequently, the phenomenon of moisture migration is encouraged.

2.5 Stowage Regulations

The irrelevance of surface ventilation to the carriage of grain is apparent from the stowage regulations in force in all major grain exporting countries, which insist that the vessel is stowed so that shifting of the cargo is impossible. Under these regulations, a ship's grain carrying compartments are classified as either partly filled or full. Grain in partly filled compartments must be levelled and topped off with bagged grain or other suitable cargo, tightly stowed and extending to a height of 1–2 m above the bulk. The bagged grain or other suitable cargo must itself be supported by a platform made either of close boarded wood or strong separation cloths laid over the whole surface of the bulk cargo.

These regulations also mean that, in compartments totally filled with grain, the grain must be trimmed to fill all the spaces between the beams, in the wings and ends.

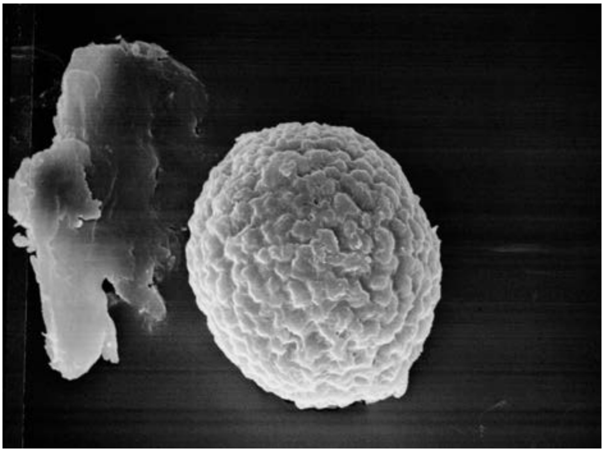
Further, to ensure that the compartment is maintained fully filled during the voyage, the compartment must be equipped with a feeder from which grain can flow into the compartment if the cargo settles during the voyage. Alternatively, the grain in the area of the hatch may be trimmed hard up to the deckhead beyond the hatchway to form a saucer. This saucer and the hatchway above are then filled with bagged grain or other suitable cargo extending to a height of at least 2 m in the centre of the saucer. The bagged grain or other suitable cargo must itself be stowed tightly against the deckhead as well as the longitudinal bulkheads, the hatch beams and hatch coamings.

The express purpose of the regulations is to reduce to a minimum, and if possible to eliminate, the headspace between the surface of the cargo and the overlying deck. With cargo stowed correctly in this way, there is no possibility of effective surface ventilation.

2.6 Karnal Bunt

Karnal bunt is a fungal disease that affects certain types of cereal grains such as wheat. The disease develops during the growth phase of the plant and not during post-harvest storage or transportation. However, it can cause potentially serious problems for shipowners and charterers. Many countries prohibit the importation of wheat that is known or, in some instances, is suspected to be affected by Karnal bunt. This can cause lengthy delays to ships while a solution is found for the disposal of the cargo. Definitive identification of the spores of the specific fungus that causes Karnal bunt in a consignment of grain requires specialised and time-consuming test procedures, which can take up to two weeks to complete.

Karnal bunt was first described in Karnal, India in 1931. It has now been identified in all of the major wheat producing regions of India, Pakistan, Iraq and Afghanistan and is also well established in north-western Mexico. More recently, it has also been found in durum wheat from Arizona. Following this discovery, a flurry of surveys and inspections was carried out, resulting in quarantine measures being imposed in the state of Arizona and in counties in New Mexico, Texas and California.



Courtesy of US Department of Agriculture

Figure 2.7: A Karnal bunt spore.

While the disease is not particularly damaging in terms of yield loss, it can cause significant reductions in grain quality. The spores of the infecting fungus are believed to present no health risks to consumers through infected grain or grain products, but wheat containing more than 3% of 'bunted' kernels is commonly considered to be unfit for human consumption. This is because flour produced from wheat containing a significant number of bunted kernels may have a distinctive odour.

Karnal bunt is also known as partial bunt. The fungal organism responsible for the disease is *Tilletia indica*. Spread of the disease occurs by the microscopically small spores of the fungus being distributed by wind and then infecting the host plant during flowering and heading. Symptoms become visible only as the grain matures. Bunted kernels can be very difficult to detect in the field, particularly in cases of mild infection, because normally not all plants in the crop are affected. Bunted kernels, however, each contain millions of spores of the fungus, which means there is potential for further spread.

There are other types of bunt, such as common bunt (sometimes known as 'stinking smut'), which is prevalent in parts of Europe and is caused by a related fungal organism. However, these other types of bunt differ in that infection is spread by spores in the soil, rather than by the wind. This means they can be controlled relatively easily by pre-treatment of the seed with suitable anti-fungal dressings. In EU countries, however, a ban has been imposed in recent years on the application of some effective fungicides previously used to treat seed. This has been held responsible for some resurgence in the incidence of common bunt in certain parts of Europe.

Karnal bunt is much more difficult to control and there is no effective solution as yet.

A number of countries, particularly those in which wheat is a crop of major importance, are extremely concerned by the importation of wheat that is known or suspected to contain kernels affected by Karnal bunt and they regard the disease as a quarantine pest. By early 1997, some 50 countries had adopted phytosanitary measures to prevent the importation of wheat affected by Karnal bunt.

Some countries accept US wheat from quarantined areas if it is certified that the wheat has tested negative for *Tilletia indica* by laboratory analysis on both pre-harvest and pre-shipment samples. Other countries, for example Mexico, require methyl bromide fumigation prior to discharge of the cargo.

It is impossible for ships' representatives to detect, by visual inspection at loading, whether a cereal grain cargo is contaminated with diseased kernels specifically affected by Karnal bunt. However, if during loading of a grain cargo any unusual odour is detected, that may or may not be due to the presence of substantial amounts of grain severely infected with Karnal bunt, the bill of lading should be claused. Other than that, the only realistic course of action open to shipowners wishing to protect their interests as far as possible is to insist on the provision of a certificate, from an authoritative source in the country of exportation, that unequivocally confirms that the cargo is free from Karnal bunt.

It may be advisable for shipowners to avoid carrying cargoes of wheat originating from countries where Karnal bunt is known to be prevalent. This applies particularly to cargoes destined for countries known to adopt a particularly severe approach to the importation of wheat from affected countries.

When a ship has discharged a cargo known to be affected by Karnal bunt, depending on future trading patterns, it may be necessary to carry out sterilisation treatment of the relevant holds to destroy the viability of any residual spores. The following sterilisation treatments are claimed to be effective:

- Wetting all surfaces to the point of run-off with a solution of 1.5% sodium hypochlorite and water and letting stand for 15 minutes. Thereafter, the surfaces should be thoroughly washed down to minimise corrosion
- applying steam to all surfaces until the point of run-off so that a critical temperature of about 80°C is reached at the point of contact
- cleaning with a solution of hot water and detergent under a pressure of at least 2 kg per sq cm (30 pounds per sq inch) at a minimum temperature of 80°C
- fumigating with methyl bromide at a dosage of 240 kg per 1,000 m^3.

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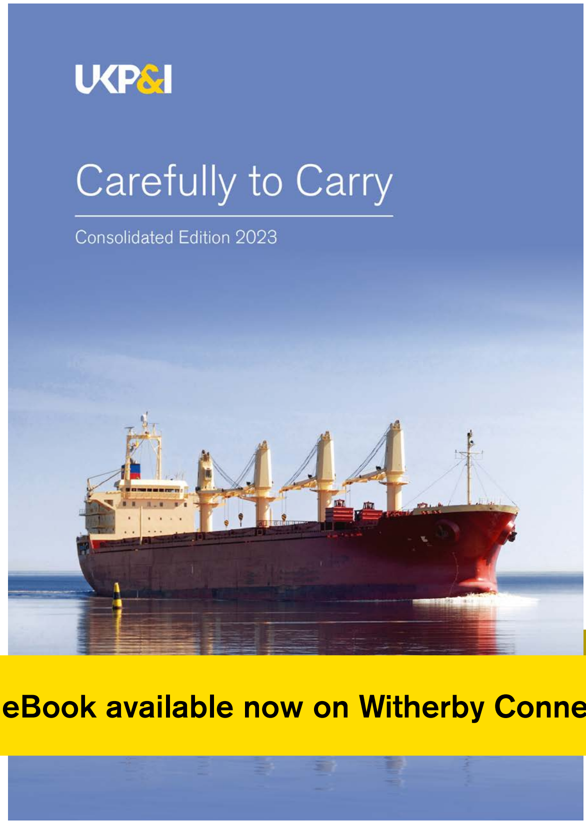

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