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SEED MOISTURE AND DRYING PRINCIPLES

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1. INTRODUCTION

This Lecture Note should be used in close connection with the Lecture Notes on seed processing and storage (C-7 and C-9).

Drying of fruits is part of the natural dispersal of many tree species. E.g. dehiscent pods and cones release their seed only upon drying.

For many orthodox (i.e. desiccation-tolerant) species this drying prepares the seeds for a period of dormancy until the next wet and warm season where they may germinate.

An example of dormancy induced by drying is the species with hard seed coats. They spread their period of germination over several seasons by drying down the seed and providing it with an impermeable seed coat. They may then rest through one or more seasons before their seed coats become permeable for water and they eventually germinate.

Maintaining the period of viability or longevity is for all orthodox species a question of reducing the activity of the seed, i.e. keeping the temperature and moisture content of the seed low.

In practice the temperature can only be controlled by keeping the fruits in well-ventilated shade or by storing the seeds in a cold store.

The moisture content can be controlled by drying. This is in most cases the simplest and safest way of prolonging the period of viability.

"Dry" is not a precise term. Seeds feel and look dry within a wide range of moisture contents. It is therefore necessary to understand and be able to control the drying processes. This Lecture Note explains the relations between moisture content of seeds and humidity of the air. It also provides methods for controlling the drying process.

It is also necessary to have reliable methods for determining the moisture content. Lecture Note C-8 on seed testing deals with sampling and determination of moisture content.

2. THE MOISTURE CONTENT OF SEED

A seed can be regarded as a structure composed of complex substances such as carbohydrates, protein and oil, with some water in addition. This water is variable in quantity - it can be added to or removed.

If a seed is placed in water, it will absorb water, thus increasing its moisture content; if it is taken out of the water, the seed will dry, i.e. water will evaporate and the moisture content of the seed will fall.

Water molecules are always in a state of vibration. If they are near the surface of the seed, they will occasionally escape into the air; this is evaporation. Similarly, the water molecules in the air are vibrating, some of them come into contact with the seed and enter into it; this is absorption. These two processes, evaporation (desorption) and absorption, are going on continuously. When evaporation exceeds absorption, the seed dries out; when absorption exceeds evaporation, the seed increases its moisture content. In an intermediate condition, evaporation and absorption are equal and the moisture content of the seed is then said to be in equilibrium with the humidity of the air.

According to ISTA rules the moisture content of seed is expressed as the weight of water contained as a percentage of the total weight of the seed before drying (percentage wet weight).

\[
\% \text{ Moisture content of seed} = \frac{\text{weight of water}}{\text{weight of sample before drying}} \times 100
\]

See section on determination of moisture content in Lecture Note C-8 on seed testing.
3. THE HUMIDITY OF THE AIR

3.1. The absolute humidity of air

On a warm day when the sun is shining, the air may be dry and you can dry your seeds as you can dry your laundry. During the night the temperature falls and you may see mist or dew in the morning. Moisture evaporated during the day and condensed as dew during the night when the temperature was low. When the temperature rises again, the mist will disappear i.e. evaporate.

The water molecules are in a state of vibration and the speed with which they vibrate is what we measure as their temperature; the faster they vibrate, the higher the temperature.

The water molecules are dipoles; i.e. we can regard them as small magnets with a positive charge at one end and a negative at the opposite end. As the molecules are dipoles, they will behave just like magnets; they will try to connect to each other in long chains, positive to negative and so on. When the molecules are connected to each other in chains, the water is in liquid form. But their vibration will continuously tear them loose from the chains again. When they are free, they will be in vapour form. When water evaporates, the water vapour is dispersed into the air as a gas with its own partial pressure.

Now consider a closed container partly filled with water. When the container is left for a while, an intermediate condition will arise: there will be an equilibrium between the amount of molecules tearing themselves loose and going into vapour form (evaporating), and the amount of molecules coming into contact with the water and "connecting" to liquid form (condensating).

At which amount of freely vibrating molecules the equilibrium will establish itself depends on how vigorously the molecules are vibrating, i.e. the temperature. At a higher temperature more molecules will escape into vapour form. Consequently the amount of free molecules per unit volume of air, i.e. the vapour pressure, will have to be higher before an equilibrium is reached. When the equilibrium is reached, the maximum possible amount of molecules is in vapour form within the container at that temperature.

The maximum amount of water vapour that can be contained in a given volume of air is limited. The amount depends on the temperature; the higher the temperature, the more water vapour.

Under ambient conditions there will not always be the maximum possible amount of water vapour present. If the temperature has recently been raised, more water will not yet have had time to evaporate. Or, in a dry climate, there may not be water available in the area for evaporation.

Under ambient conditions the water vapour will occupy the given volume together with air and have the same temperature as the air. So for practical purposes the water vapour is described in relation to the air it is dispersed within:

The absolute humidity of air is the amount of water vapour present in the air. It is usually measured in kg water per kg dry air.

In this Lecture Note grammes (g) of water vapour per kg air will is used. In the following the water vapour is also described as “contained” by the air. As explained above this is not true; the water vapour is only dependent on its own partial pressure and temperature. But using the term may ease explanation and understanding.

When the air contains the maximum amount of water vapour, it is said to be saturated. As already explained, the amount of water the air will contain depends on the temperature of the air. So if you lower the temperature of air containing any amount of water vapour, you will, as cold air will contain less water than warm air, sooner or later reach a point where the air is saturated. If you continue to lower the temperature of the saturated air, some water vapour will condense. You may see this as water on the surface of cold things or as mist or dew in the morning when the temperature has been low during the night.

The temperature at which the air is saturated with water vapour and condensation starts depends on the amount of water vapour present in the air. It is called the dew-point temperature.
Or:
The dew-point temperature depends on the amount of water vapour actually present in the air. The greater the amount of water in the air, the higher the dew-point temperature. E.g. air with 5 g water vapour per kg dry air will reach dew point when cooled to 4°C, while air with 20 g water/kg dry air will reach dew point already at 25°C.

Air and water vapour expands when the temperature rises (approx 10% for every 27°C). For this reason the absolute humidity is expressed as g water per kg dry air instead of g water per cubic metre of air. Table I gives the weight of dry air (γ) per cubic metre at a number of temperatures (t). The table also gives weight of water vapour (xs) present in saturated air at the same temperatures.

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<tr>
<th>Temperature t °C</th>
<th>Weight of dry air γ kg/m³</th>
<th>Weight of water vapour in saturated air xs g/kg air</th>
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Figure 1. Weight of water vapour (per kg dry air) in saturated air at different temperatures.
As it can be seen from Table I and Figure 1, the amount of water vapour present in saturated air increases drastically with temperature.

3.2. The relative humidity of air

Hot air with 20g water/kg dry air is saturated and reaches dew point when the temperature falls to 25°C. We say that the relative humidity of this air is 100% at 25°C. If air only contains half as much water vapour, 10g water/kg dry air, then the relative humidity is 50% at 25°C. The relative humidity is the amount of water vapour present as a percentage of the amount in saturated air at the same temperature. Or for drying purposes:

The relative humidity of air is expressed as the amount of water vapour present as a percentage of the maximum amount of water vapour air can contain at the given temperature.

The relative humidity can be changed in two ways: (A) by changing the amount of vapour in the volume, (B) or by changing the temperature.

(A) if more water vapour is added to the air, the total amount present in the air will increase and get closer to the amount present in saturated air. I.e. both the absolute and the relative humidity will increase;

(B) if the temperature is raised, a larger amount of water vapour can be present before the air is saturated at the higher temperature, and the difference between the actual amount present and the amount present at saturation will increase. I.e. the absolute humidity will remain the same but the relative humidity will fall if the temperature is raised.

The relative humidity may be a more difficult term to operate with than the absolute humidity. But, as stated in chapter 2, the equilibrium moisture content the seed reaches is dependent on the humidity of the air, i.e. the vapour pressure. The absolute humidity describes the amount of water present (in g water per kg dry air) regardless of temperature, but the relative humidity describes the actual pressure of this vapour at the given temperature. And thus for drying purposes tells us if the seed will dry or absorb water in this air.

In the following a graphical description of the relationship between absolute humidity, temperature and relative humidity, the I-X-diagram, is presented. Afterwards the relationship between the relative humidity and the moisture content of seeds will be discussed.
3.3. The I-X-diagram

When the curves for every 10% decrease in relative humidity is placed in the same kind of graph as Figure 1, the diagram will look as in Figure 2.

**Figure 2.** Relationship between absolute humidity, temperature, and relative humidity.

The diagram describes the relationships between (A) temperature, (B) absolute humidity and (C) relative humidity at temperatures between -10°C and 60°C.

(A) The temperature of the air in °C is shown by the horizontal lines from the vertical (y-) axis.
(B) The water content of the air (the absolute humidity in g water/kg dry air) is shown by the vertical lines from the horizontal (x-) axis.
(C) The relative humidity (RH) is represented by the curved lines. The lowest curve, RH = 100%, is the temperature/water content combination at which the air is saturated (the dew point).

This kind of diagram is a powerful tool when working with drying, storage and assessment of moisture content. To give you an idea of how useful this diagram is, the following examples are given:
Example 1:

In a greenhouse with little or no air exchange, air at 26°C with 70% relative humidity is heated during daylight to 35°C by the sun. The steps explained below are shown in Figure 3 by arrows and numbers.

1) At 26°C and 70% relative humidity the water content of the air is 15 g water/kg dry air.
2) When the temperature rises, the water content (i.e. the absolute humidity) will remain the same, but as the air can hold more water at the higher temperature, the relative humidity will drop. If you follow the vertical line for 15 g water/kg dry air till it intersects with 35°C, the diagram in the figure shows you that the relative humidity is now 42%.
3) If we keep the air at 35°C, 42% relative humidity may be too low for the plants in the greenhouse. Suppose we have to apply mist irrigation to evaporate water until the relative humidity is 70% again. The figure shows that at 35°C the relative humidity will be 70% when the absolute humidity is 25 g water/kg dry air, so 25-15 = 10 g water/kg dry air will have to be applied before the air has regained a relative humidity of 70%.

Cubic metre (m³) air is in many cases a more convenient factor than kg dry air. As can be seen from Table I, the density of air is approx 1.145 kg/m³ at 35°C. In this case 10 g water/kg dry air equals 10 g/kg * 1.145kg/m³ = 11.5g/m³.

Example 2:

If the door to a cold store at 4°C is opened, some heavy cold air (with high density) floats out and some warm air gets into the cold store. If the air from outside the store is e.g. 25°C and has 75% relative humidity, the following will happen in the cold store when the door is closed and the air from outside is cooled:

The steps explained below are shown in Figure 4 by arrows and numbers.
1) At 25°C and 75% relative humidity the air contains 15 g water vapour/kg dry air.

2) When the air gets colder the relative humidity will rise. With 15 g water/kg dry air the dew point (and 100% relative humidity) is reached at 20°C, and water will start to condensate when the temperature gets below 20°C.

3) At 4°C the vapour is saturated with only 5 g water/kg dry air, which means that 15-5g = 10 g water per kg dry air that got into the store will condensate in there.

Initially there is condensation on all cold surfaces, just like on a bottle taken out of the refrigerator. As the cold store is constantly being heated by the surroundings even if the insulation is good, there will always be a couple of degrees difference in temperature between the cooling elements (called evaporators because the cooling fluid evaporates inside them) and the other areas of the cold store. If the evaporators are running at 4°C, the average air temperature in the cold store is 6°C. The relative humidity on the surface of the evaporators is 100% as the water is condensing there, and the relative

4) humidity of the air will fall to 85% as the air circulates in the store.

So later the condensated water on all the cold surfaces will evaporate again and condensate on the evaporators. From there it is usually collected in a tray and led through a hose to the outside of the cold store.

If the evaporators had a surface temperature below 0°C, then the water would condense as ice and the evaporators would have to be reheated periodically to melt the ice so that the water could run out of the cold store.

5) (If air from the cold store were led into a closed container outside and allowed to reheat to the ambient 25°C there, then the relative humidity would drop to 26%, which is very dry air).

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**Figure 4.** see example 2 for explanation.
The relative humidity of a place can be measured by a psychrometer. Two thermometers are placed next to each other and the bulb of one of them is kept moist inside a thin wick. The wick should be placed like a stocking around the bulb with the other end dipped in water, so that the temperature of the water and air on the surface of the wick is measured. The other thermometer should be kept dry, and both should be placed so that the air has free access.

Water evaporates from the wet bulb until the relative humidity on the surface of the wick is 100%. Energy is consumed for the evaporation, and as no energy is supplied from outside, the temperature will fall. The drier the air, i.e. the lower the relative humidity of the air, the more water will evaporate and thus the larger the temperature drop.

The diagonal lines sloping down from the vertical (y-) axis added to the diagram in Figure 6 indicates the energy (in kJ/kg air) necessary for heating air and its moisture content from dry air at 0°C to a given temperature and moisture content of the air. The lines therefore represent the energy content of the mixture of air and water vapour at different temperature / humidity conditions. With these lines added, the diagram is generally known as an I-X-diagram. A complete I-X-diagram is presented in Appendix 1.

Example 3:
With the help of the I-X-diagram it is possible to find the relative humidity of the air.

Let us take the example that the dry thermometer shows 20°C and the wet 14.4°C. The steps explained below are shown in Figure 6 by arrows and numbers.

1) If we look at the I-X-diagram in Figure 6 at 14.4°C, 100% relative humidity and follow the diagonal line indicating the same energy content until it intersects with 20°C, the figure shows that the relative humidity is 55%.
Measurements of the relative humidity with a wet and dry bulb thermometer (a psychrometer) is only valid if the volume of ambient air is so large that the evaporated water from the wet bulb does not affect the relative humidity significantly. The air also has to circulate so that the humid air around the wet bulb is constantly exchanged with dry air so that water keeps evaporating from the wet bulb. A light draught (1 m/sec) is sufficient.

Alternative ways of measuring the relative humidity are 1) the hair hygrometers described in example 6, and hygrometers based on changing electrical properties usually with electronic processing and digital display.

Figure 6. See example 3 for explanation.
4. THE RELATIONSHIP BETWEEN MOISTURE CONTENT OF SEED AND RELATIVE HUMIDITY OF THE AIR

4.1. Equilibrium moisture content of seed

Seed, wood and many other materials contain water. We may dry them and remoisten them i.e. the materials desorb (dry) and absorb water.

Seed will dry or absorb water until it reaches an equilibrium moisture content with the relative humidity of the surrounding air. This relative humidity, where the moisture content of the seed is stable, is called the equilibrium relative humidity.

Example 4:
Two samples of the same seed lot placed at 30°C, 20% relative humidity and 40°C, 20% relative humidity respectively will dry down to approximately the same moisture content. The only difference is that the sample at 40°C will dry faster because of the higher temperature.

4.2. The sorption isotherms

The equilibrium moisture content that seed reaches at different relative humidities can be displayed as a graph. An example is shown in Figure 7. Here the curve indicates which moisture content moist wheat with 2% oil content will dry down to if kept at different relative humidities and 35°C.

The curve indicating equilibrium moisture content, will not always be exactly identical. It will vary: depending on (A) species, (B) temperature and (C) it will also vary slightly depending on whether the seed is drying or absorbing moisture from the surrounding air:

(A) Seeds consist of carbohydrates (e.g. starch), proteins and oils, but practically only the carbohydrates and proteins can absorb water.

Take e.g. a seed with a high oil content of 50%. If the moisture content of the seed is measured to be 8% moisture content by the oven method prescribed by ISTA, and all the moisture is absorbed in the carbohydrates and proteins of the seed then, as the moisture content is measured on basis of the weight of the whole seed, the actual moisture content of the carbohydrates and proteins occupying half of the seed weight is 16%.

When the carbohydrates and proteins of the same seed are dried down to be in equilibrium at 8% moisture content, an oven test of the moisture content would show 4% moisture content of the whole seed.

The curve indicating equilibrium moisture content of seeds with a high oil content will therefore be lower than a curve for seed with low oil content.

(B) A rise in temperature will increase the speed of vibration of the water molecules. They will therefore be more liable to evaporate and the seed will be in equilibrium at a lower moisture content. In practice the curves are approximately 1% moisture content lower per 10°C rise in temperature.

Figure 7. Equilibrium moisture content of wheat with 2% oil content at 35°C.
If the relative humidity around a seed at equilibrium moisture content is raised, then there has to be a certain difference in relative humidities before the seed starts absorbing moisture. This difference in desorption and absorption curves is called hysteresis. For drying curves (desorption) the equilibrium moisture content are 1-2% higher at a given relative humidity than for the absorption curves, where the seed picks up moisture.

These curves indicating equilibrium moisture contents at different conditions are known as sorption isotherms. They can e.g. be used to estimate to which moisture content seed can be dried in a given climate.

In Appendix 2 and the examples below some general sorption isotherms based on data from various sources are given. The sorption isotherm for silica gel is also shown as it is a very useful regenerable desiccant for small amounts of seed (see 5.6.2.). The points A-C above should be noted when using the sorption isotherms as drying curves.

Example 5:
When moist wheat is placed at 35°C and 40% relative humidity, and the air is constantly renewed so that the relative humidity stays at 40%, then the moisture content of the wheat will drop to an equilibrium moisture content of 9.8%.

The speed of absorption or desorption depends on temperature, speed of airflow, how permeable the seed coat is, relative humidity of the air, and moisture content of the seed. The time needed to reach equilibrium may be anywhere between 1 day and 3 weeks.

Example 6:
When dry wheat is placed in a sealed plastic bag with a calibrated hair hygrometer and the hygrometer comes to a rest showing 25% relative humidity after approx 15 hours at stable room temperature (approx. 20°C), then the moisture content of the seed is approx 7.5%.

![Sorption isotherms. Moisture content (% wet weight) in equilibrium with relative humidities (extracted from Roberts 1972).](image-url)

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1Hair hygrometer: A hair (human or horse) contracts when dried. One end of the hair is connected to a fixed point in the instrument, the other end is connected to a needle on a scale showing the relative humidity.

To calibrate a hair hygrometer it is placed under a moist cloth in the shade for half a hour. The hygrometer is then adjusted to approx. 95% relative humidity. Check again that the hygrometer remains showing 95% relative humidity under the moist cloth.

Air contains small oil particles. These adhere to the hair in the hygrometer and prevents the hair from absorbing moisture. So depending on working conditions, the hygrometer should every month or half year be cleaned by washing in benzine. Agitate the hygrometer in a bowl with benzine. Do not let the benzine get in contact with your skin.
If you intend to use this method to determine moisture content with reasonable accuracy in seed centre routine or as a field method, it would be necessary to calibrate sorption isotherms for the commonly used species. This is done by measuring the moisture content of seeds at equilibrium with known relative humidities. Measurement of the moisture content by the ISTA oven method and calibration is described in Lecture Note C-8 on seed testing and Technical Note No. 37 on moisture content and calibration of moisture metres.

DFSC would be very interested in receiving copies of sorption isotherms of tropical tree species.

5. SEED DRYING

5.1. Principles of seed drying

Normally, all fruits have a variable but high moisture content at the time of their full ripeness. Under normal conditions the orthodox species will mature during the dry season allowing the local weather to dry the fruits and seeds. Indigenous recalcitrant species on the other hand very often mature during a moist season to prevent the seed from drying out and to allow it to germinate before a dry season.

Examples of seed drying will be given in the following. There is no difference between fruits and seeds in the procedures for drying, except for the fact that fruits are usually more bulky than seed.

The storability of fully ripe orthodox seed usually benefits from drying down to 6-8% moisture content. This is in many cases lower than the moisture content the seed naturally would reach. To reach this low moisture content you will have to create a sufficiently low relative humidity in the air surrounding the seed. When moisture evaporating from the seed raises the relative humidity around the seeds, the air will have to be changed with new air with a sufficiently low relative humidity, e.g. by the wind.

**The speed of drying is determined mainly by:** (A) the speed with which the moisture can migrate to the surface of the seed for evaporation, (B) the air velocity around the seed, (C) the temperature, and (D) the relative humidity.

(A) The speed with which the moisture can migrate to the surface of the seed for evaporation: in practice the density and thickness of the seed coat often determines how fast the moisture can migrate to the surface of the seed.

On the other hand, if the seed coat is porous and the surface of the seeds dry faster than the moisture can migrate out through the seed, the outer layers of the seed may dry out and perhaps collapse trapping moisture inside the seed. This will prevent any further drying and may present a risk to the viability. Immature fruits, e.g. green cones that have not turned sufficiently brown, may prevent drying by “case hardening” of the outer layers.

In these cases the only option is to remoisten the seeds or fruits, let them complete the ripening process and repair damages inflicted by the collapse of tissue in a cool environment, and repeat the drying process at a lower rate.

(B) Air velocity: the drying time is approximately halved when the velocity of the air around the seed is doubled. The upper limits are the speed of available fans (or the velocity of natural wind), practical limits to how thin the layer of seed can be, and the point when the air starts moving the seed.

(C) Temperature: a rise in temperature accelerates the drying process at a given relative humidity. Water evaporates more easily at a higher temperature, a rise of 10°C approximately doubles the speed. In addition, raising the temperature of the drying air also lowers the relative humidity. Most drying processes use a high temperature to achieve a low relative humidity, which again accelerates the drying process.

The maximum temperature that the seeds will tolerate depends on species and how dry the seed is. Until specific temperatures for your species have been established, safe drying temperatures for most orthodox species are 35°C until the moisture content is below 15%. Below 15% moisture content the temperature can be raised to 45°C.

Some typical safe drying temperatures for agricultural species are as follows (Roberts 1972): Cereals like oats and wheat can tolerate 45°C at 30% moisture content progressing to 65°C at 18% moisture content whereas...
peas and clover will tolerate only 28°C above 20% moisture content and 38°C from 20 to 12% moisture content. (It should be noted that some species seemingly have curves reverse to the normal, e.g. rice will tolerate 60°C above 20% moisture content, 52°C between 20 and 15% moisture content, and 50°C below 15% moisture content).

The air temperature that the seeds can tolerate also depends on rate of drying since evaporation cools the seed and, if energy input is kept constant, the temperature of the seeds themselves will be lower than the air temperature (cf. the wet bulb of the psychrometer in example 3).

In this connection you should note that a high temperature also increases the respiration and ageing process. This implies that the period during which the seed is subjected to a high temperature should be kept as short as possible, i.e. the relative humidity should be kept as low as possible by ensuring sufficient ventilation.

(D) The difference between equilibrium relative humidity and relative humidity: the relative humidity of the air should under the whole process be lower than the equilibrium relative humidity corresponding to the moisture content of the seeds. The equilibrium relative humidity can be found from the sorption isotherms (see Figure 8 and appendix 2). The speed of drying will be high if the relative humidity of the drying air is low compared to the equilibrium relative humidity as each unit of air can carry away more water. Thus if the same relative humidity and temperature is maintained during the drying process, the speed of drying will decrease as the seed moisture content is reduced.

Example 7:
Wheat is to be dried down to 6% moisture content in a climate like that of Morogoro, Tanzania:

Assume that safe drying temperature is not known, and that we will have to use 35°C while the moisture content is still above 15% and 45°C when the moisture content is below 15%.

The first step is to bring the moisture content down below 15% without exceeding 35°C:
From the sorption isotherms (Figure 8 or appendix 2) we find that the equilibrium relative humidity at 15% moisture content at desorption at 35°C is 80% relative humidity.

Climatic data for the drying location is shown in Table II taken from: World survey of climatology, vol 10; climates of Africa.

### Table II:

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<td>37</td>
<td>9</td>
<td>20</td>
</tr>
</tbody>
</table>

Years of recording

15 15 15 15 15 15 57 57 57 57 57 57 14 14 14 14 14 14 16 16
The steps explained below are shown in Figure 9 by arrows and numbers.

At Morogoro the dew-point temperature lies between 22 and 16°C, which
1) means that the water-vapour content lies between 16.5 g and
2) 11.5 g per kg dry air,
3) and that the relative humidity at 35°C lies between 32%
4) and 47%.

As these relative humidities are well below the required equilibrium relative humidity of 80%, it will be possible to bring the moisture content of the seed down to 15% by good ventilation only.

5) In the dry season, the drying temperature may go right down to 20°C while
6) in the wet season the temperature may go down to 25.5°C.
When the drying temperature is allowed to fall further (e.g. during the night), the relative humidity will rise to above the 80% and the seed will start to absorb moisture again.

The second step is to bring the moisture content down to 6% without exceeding 45°C. Again we go to the sorption isotherms and find that the equilibrium relative humidity to 6% moisture content at 45°C is 15% relative humidity at desorption.

7) From the I-X-diagram we find that air at 45°C with 15% relative humidity has dewpoint at 12.5°C and contains 9 g water per kg dry air.
8) As the water-vapour content at Morogoro lies between 11.5 and 16.5 g per kg dry air, the diagram shows that 15% relative humidity can only be reached by raising the temperature above 50°C.

Figure 9. See example 7 for explanation.
As the safe drying temperature is 45°C, we are left with 3 options:

1) The drying air may be artificially predried in a closed space. Either by cooling it down to below 12.5°C, by which some of the water condensates and can be removed, and then reheat the now drier air until 15% relative humidity is reached, or by desiccating the air with a chemical desiccant, see 5.6.2.

2) If a higher temperature is considered safe when the seed is very dry, the following steps can be taken presuming it is October and the dew-point temperature is 18°C in Morogoro. Heating the drying air to 45°C will reduce the relative humidity to 22% and the seed will eventually reach an equilibrium moisture content of 6.9%. Once this is done, it is necessary to raise the drying temperature to reach the 15% relative humidity.

QUESTION: At which temperature will the relative humidity be 15%?

3) The temperature which is necessary in order to reach 15% relative humidity depends on the actual dew-point temperature (the actual dew-point temperature can be measured on a well ventilated wet bulb thermometer in the shade, see example 3). If this temperature is considered too high to be safe, and equipment for artificial predrying is not available, one will have to accept a higher moisture content of the seed under storage, in this case 6.9% moisture content (cf. 2) above).

The following connections between dew-point temperature and obtainable moisture content in seeds in drying air at 45°C can be found by extrapolation from the I-X-diagram and sorption isotherms in appendices 1 and 2.

<table>
<thead>
<tr>
<th>dew point temperature</th>
<th>relative humidity</th>
<th>moisture content % of wheat at 45°C, desorption</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>14</td>
<td>5.9</td>
</tr>
<tr>
<td>14</td>
<td>17</td>
<td>6.2</td>
</tr>
<tr>
<td>16</td>
<td>19</td>
<td>6.5</td>
</tr>
<tr>
<td>18</td>
<td>22</td>
<td>6.9</td>
</tr>
<tr>
<td>20</td>
<td>25</td>
<td>7.2</td>
</tr>
<tr>
<td>22</td>
<td>27</td>
<td>7.5</td>
</tr>
<tr>
<td>24</td>
<td>31</td>
<td>8.0</td>
</tr>
<tr>
<td>26</td>
<td>35</td>
<td>8.4</td>
</tr>
</tbody>
</table>

Climatic data such as those presented above for Morogoro in Tanzania can be obtained from local meteorological institutes.

It is important that seed is sufficiently dry before storing. A lot of seed is stored with too high moisture content. Reduction in viability (and loss of total value) when the seed is stored at a high moisture content should be compared to the cost of drying plus the smaller reduction in viability when the seed is stored at a lower moisture content.

E.g. cost of procuring 1 kg seed at 10% moisture content 300 $  
cost of additional drying to 6% moisture content 20 $  
If stored for 1.5 years at 10% moisture content, there may be a reduction from 100% germination to 70% germination, i.e. a loss of 30/100 * 300 $ = 90 $  
If stored for 1.5 years at 6% moisture content, there may be a reduction from 100% germination to 95% germination, i.e. a loss of 5/100 * 300 $ + 20 $ for additional drying = 35 $

The time needed for drying can be estimated from local experience but a routine check on moisture content before storage is necessary, see Lecture Note C-8 on seed testing.
5.2. Drying in the shade

Drying in the shade can be advantageous under some circumstances:

The high temperatures in the sun can damage seeds with high moisture content.

The seed cannot after-ripen and heal mechanical damage once the moisture content is lower than 15-20%.

If the seed is not fully ripe, a slow drying process will permit the seed to complete the ripening processes and be ready for storage and germination.

There must be adequate ventilation as high relative humidity will promote fungus and insect attack. Well ventilated covered walkways or open sheds where driving rain cannot enter are normally used for drying seed or fruit in gunny bags, e.g. after-ripening of pine cones.

A more sophisticated arrangement for drying in the shade consists of a well-ventilated room and stacks of shelves with trays with wire mesh bottom. The fruits are spread in a thin layer in the trays and stirred regularly. This arrangement is useful for seeds of species which can easily be damaged by heating in the sun or kilns, and for species which need to be stored at relatively high moisture content in order to retain viability. See Lecture Note C-6 on seed handling prior to processing.

![Figure 10. Cones in gunny bags on a covered walkway](image)
5.3. Drying in the sun

The sun raises the temperature, thus lowering the relative humidity in the air around the seed. As the air around the seed has a limited moisture carrying capacity, it is necessary to ensure adequate air flow around the seed.

The moisture content of the seed will come to rest at an equilibrium moisture content corresponding to somewhere between the day and night relative humidity around the seed.

Example 8:
A batch of seed gets 4 hours of direct sunlight a day raising the temperature to 40°C, the average seed temperature the rest of the day and night is 22°C, and the dew-point temperature is 18°C.

The relative humidity in the sun will be 28% and the rest of the day and night approx. 78% (I-X-diagram: dewpoint at 18°C, raise the temperature to 40°C and 22°C).

The seed will normally not come down to the equilibrium moisture content corresponding to 28% relative humidity during the 4 hours in the sun and will certainly absorb moisture again during the night. The moisture content in the end will be somewhere between the equilibrium moisture contents corresponding to 28% and 78% relative humidity, depending on how good ventilation is during high-temperature hours and how effectively ventilation is shut off during low-temperature hours once the seed has a moisture content lower than the equilibrium moisture content to 78% relative humidity.

(QUESTION: What is the equilibrium moisture content to 28 and 78% relative humidity ?)

The essentials in sun drying are:

1. To ensure as many hours as possible in the sun (avoiding shade).
2. To allow free access of the wind to a thin layer of seed (if necessary, erect a mobile windbreak to prevent the seed from blowing away on windy days rather than having an inefficient drying area on calm days).
3. To prevent the seed from absorbing moisture during the night or when the relative humidity is high. E.g. cover with a tarpaulin against dew, rain and humid air flow, and store indoors or in airtight containers when the moisture content of the seed is so low that absorption cannot otherwise be prevented during hours without sun.
4. To prevent overheating while the seed still has a high moisture content. If the moisture content of the seed is above e.g. 15-20%, initiate drying in the shade and transfer the seed to the sun when the moisture content is below 15%. High temperature and moisture content together accelerates respiration and imposes stress to the seed; see also 5.1.
5. To remove any seed which has separated from the fruits in order to prevent unnecessary exposure to high temperatures during extraction.

In the tropics nearly all seed is dried in the sun. Either in flat baskets or trays, or on concrete decks or tarpaulins. Under most conditions this is the most convenient and cheapest form of drying.

The actual temperature reached during sun drying will be dependent on many factors and vary from day to day and during the day. The temperature can be monitored by placing a thermometer just under the surface of the seeds so that the sun does not reach the bulb.

In the dry season most sun-dried seed will reach a moisture content of approx. 8%. A moisture content of 8% is under most circumstances a sufficiently low moisture content for short-term storage (1-3 years) under ambient temperatures, and also sufficient for medium-term storage (5-10 years) at below 5°C.

DFSC Technical Notes no. 9, 17 and 22 describe cone drying and extraction methods.
5.4. Drying under transparent cover

Forced drying under transparent cover is normally done in trays or concrete frames with a transparent cover of polythene sheeting.

The high-frequency sun rays can pass through transparent materials like polythene or glass but when they hit solid materials like cones or seed, they are converted into low-frequency heat rays which cannot pass through glass or polythene sheeting.

Thus the temperature under transparent cover will be higher, lowering the initial relative humidity. To take advantage of this it is however necessary to ensure the right amount of ventilation under the cover to keep the relative humidity low and not lower the temperature too much. If the ventilation is inadequate, the seed will just be subjected to a higher temperature shortening the life-span without effectively speeding up the drying process. If the rate of air exchange is too high, some effect of the transparent cover on temperature will be lost.

Example 9:

20 kg of wheat is to be dried down from 12% moisture content to 6% moisture content under transparent cover and the dew-point temperature is 17°C.

In the beginning of the drying process the moisture content is 12% and the equilibrium relative humidity will be 65% relative humidity. At a temperature of e.g. 45°C air can hold 41g water/kg before it reaches 65% relative humidity (see diagrams). As the air enters under the cover with 12g water/kg (dewpoint 17°C) it will remove

\[(41g - 12g)/kg \text{ air} = 29g \text{ water/kg air or}\]

\[29g/kg \times 1.2 \text{ kg/m}^3 = 35g \text{ water/m}^3 \text{ air}\]

before it has reached 65% relative humidity (see example 1).

But in the end of the drying process the temperature will have to be raised to e.g. 55°C as the equilibrium relative humidity to 6% moisture content is about 17% relative humidity, and air with dew-point at 17°C will reach 17% relative humidity at about 50°C.

If the air is 55°C and has 17% relative humidity when leaving the cover, it contains 17 g water/kg.

\[(17 - 12)g \times 1.2 \text{ kg/m}^3 = 4.8g \text{ water/m}^3 \text{ air} \text{ has then been removed.}\]

As the 20 kg of wheat was to be dried from 12% moisture content to 6% moisture content, 1200 g water will have to be removed. The amount of water removed ranges from 35 g/m³ air in the beginning to 4.8 g/m³ in the end.

From the example it can be seen that the art of drying under transparent cover consists of:

1) Monitoring dew-point temperature, temperature under the cover, relative humidity under the cover, and the moisture content of the seed.

2) Ensuring sufficient ventilation (in the example at least 200 m³ of air will have to pass under the cover).

i.e. the temperature under the cover should not be kept down by shading but by better ventilation.
During the night it should be possible to close the covered frames completely to prevent the seed from absorbing moisture when the moisture content of the seed is lower than the equilibrium moisture content corresponding to the relative humidity of the night air.

Practical applications of drying under cover range from erecting tent-like structures of clear polythene over seeds spread out on the ground, and for small lots covered trays (Figure 11), via covered sheds (Figure 12) to solar timber drying kilns as the one described below (Figure 13).

**Figure 11.** Example of drying tray with transparent cover.

**Figure 12.** Extraction sheds in Zimbabwe: a wire netting-base which can be lined with hessian, roofed with clear polythene sheeting.
The Nomad Solar Kiln consists of an aluminium frame covered with a polyester glazing film. Solar heat is absorbed by a false ceiling of sheets of black corrugated iron. Fans using 7.5 kW on 10 hours’ running per day circulate air inside the kiln. For further information write Oxford Forestry Institute or Cambridge Glasshouse CO. Ltd., Comberton, Cambridge CB3 7BY, ENGLAND.

5.5. Kiln drying

The idea of kiln drying involves basically the same procedures as already described. The air inside the kiln is heated to reduce the relative humidity and is circulated with fans to speed up the evaporation. When the relative humidity rises from the evaporated water, vents are opened allowing air exchange. A seed or cone drying kiln should be constructed so that temperature, air exchange and relative humidity are easy to control. The internal air circulation should have the highest possible speed.

Figure 13. Cross cut section of the nomad solar kiln.

Your local wood technology institute should have knowledge of kiln construction and operation from timber drying.
A very simple version of kiln drying for small seed lots is an arrangement with an adjustable lamp with a reasonably high watt bulb and a small electric fan.

Another simple version of kiln drying is the following: Stackable wire netted trays are placed on top of each other and covered with e.g. a tarpaulin to form a chimney. A heating unit consisting of a centrifugal fan and an electrical heating element is connected with the bottom of the chimney. Arrangements should be made to ensure air flow and control of temperature and to avoid fire risk and loss of seed.

**Figure 15.** Kiln built with wire netted trays.
5.6. Predrying of air and vacuum drying

Drying the seed by raising the temperature of the drying air shortens the life-span of the seed. Therefore other technically more complicated methods of reducing the relative humidity without raising the temperature are under some circumstances worth considering. E.g. in the case of semi-recalcitrant seed where the life-span is short already. The idea is either to remove moisture from the drying air (by condensation with a dehumidifier or chemical sorption of the moisture), or by lowering the air pressure and thereby the vapour pressure of water (vacuum drying) if necessary in combination with temperature control.

5.6.1. Dehumidifier

A dehumidifier contains the same elements as a refrigerator or a cold store: 1) A fluid (e.g. freon) circulates in a closed system. A compressor compresses the fluid causing it to condense. The condensation process releases energy which heats the fluid. The fluid then passes through a radiator where it is cooled down to ambient temperature.

2) It then passes through a valve and evaporates in the low pressure side (the evaporator). The evaporation process consumes energy, i.e. cools the surroundings (when you put a kettle with water over fire, the energy will heat the water until it boils at 100°C, after that the energy will be used for evaporation of the water). The fluid, now in gas form, continues to the compressor where it is condensed again.

3) Air is blown through the evaporator and radiator by a fan.

The air is cooled by the evaporator forcing some of the humidity in the air to condense on the evaporator. The air then leaves the system through the radiator where it is reheated. The air will leave the system a couple of degrees warmer than it entered as it has absorbed heat released by condensation of water and the energy used by the compressor and fan. But the air will also leave the system with a lower absolute humidity, as some water vapour condensates and falls into the bucket below.

The relative humidity of the air leaving the dehumidifier will depend on the temperature of the air entering, as the dew-point temperature is fixed and depends on the kind of machinery inside the dehumidifier. In small household or office dehumidifiers the evaporator is set to work at approx. 2°C. The temperature of the air after passing through the evaporator will then be around 6°C i.e. the dew-point temperature will be 6°C. If the room temperature is 23°C then the air leaving the dehumidifier will be around 25°C and the relative humidity will be 30% (see example 2).

The equilibrium moisture content to 30% relative humidity is approx. 8% moisture content. But this is also the lowest relative humidity in the working range of small dehumidifiers at room temperature. If a lower relative humidity is needed, the working temperature must be raised, or a dehumidifier that is geared to work with the evaporator at temperatures below 0°C should be used.

**Figure 16.** Principal lay out of a dehumidifier.
The capacity of a dehumidifier depends on the size of compressor used (how many m³ of air and moisture it will cool and condense per time unit).

The capacity of a small dehumidifier fitted with a 280 W (0.38 h.p.) compressor is shown in Figure 17. This is the type normally used in offices in the humid tropics. A doubling of the compressor size will approximately double the capacity in litres of water per day.

5.6.2. Chemical drying, desiccants and sorption driers

Chemicals like silica gel and lithium chloride can ad- and ab-sorb high weight percentages of water even at low relative humidities. The chemical is dried (regenerated) by hot air. Afterwards the chemical can be used to dry the seed. The sorption isotherm of silica gel is shown in Figure 8 and appendix 2.

Two methods can be used: (1) A manual method where the chemical (desiccant) is dried in an oven and afterwards placed in a container with the seed. (2) A mechanical method where drying air is circulated through the desiccant.

For smaller seed lots silica gel is the most useful regenerable desiccant. It is dried in an oven at not above 175°C and cooled in a sealed container before use.

Example 10:
5 kg of wheat is to be dried from 8% to 6% moisture content.

\[5000 \text{ g} - (5000 \text{ g} \times 0.92/0.94) = 106 \text{ g} \text{ water is to be removed.}\]

Wheat’s equilibrium relative humidity to 6% moisture content is 10% relative humidity and silica gels equilibrium moisture content to 10% relative humidity is 5% moisture content. As the silica gel is to absorb 106 g water, \(106 \text{ g} / 0.05 = 2.12 \text{ kg}\) silica gel is necessary.

The silica gel and seed are placed in a closed container in net bags or in a desiccator until practical experience shows the seed is dry, usually 1 to 3 weeks, as the air circulation inside the container is limited. This method is limited to smaller amounts of seed as silica gel is expensive.
In mechanical sorption driers, the drying air is circulated through the desiccant alternating with a hot air stream which regenerates the desiccant. The desiccant is either placed in a number of columns which are alternately brought into the hot air stream or, as in the case of the Munters sorption drier illustrated in Figure 18, impregnated on a rotating disk placed inside a case with the two air streams passing through, one is the hot regenerating air stream, the other is the drying air.

The smallest sorption driers on the market have a capacity of 50-120 m³ drying air/hour.

The hot air stream for regeneration will heat the desiccant, which in turn will heat the drying air. This necessitates some kind of cooling of the drying air. If the sorption drier is placed in connection with a cold store, some extra cooling facility will probably have to be installed as the normal refrigeration unit in most cases will lack capacity to cool the drying air also.

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Figure 18. Working principle of a Munters sorption dryer connected to an air conditioning unit and a drying cabinet.

The smallest sorption driers on the market have a capacity of 50-120 m³ drying air/hour.

The hot air stream for regeneration will heat the desiccant, which in turn will heat the drying air. This necessitates some kind of cooling of the drying air. If the sorption drier is placed in connection with a cold store, some extra cooling facility will probably have to be installed as the normal refrigeration unit in most cases will lack capacity to cool the drying air also.

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Munters, Box 450, S-19124 Sollentuna, Sweden.
Int. telefax +46 8 7548594.
A small drying cabinet is produced by CMC Automation. It consists of a cabinet with 24 trays with wire net bottom giving a total net surface in the cabinet of 14.4 m². This gives the cabinet a capacity of around 150 kg seed depending on species. The sides and the top of the cabinet is thin metal sheeting allowing the heat produced by the drier to escape. The temperature inside the cabinet will therefore stay at 5-7°C above ambient temperature. The cabinet is equipped with a sorption drier with a capacity of 120 m³ air/hour. An average drying capacity of the cabinet at 25°C ambient temperature is around 0.7 kg water per hour.

Sorption driers are rather expensive and complicated but have the advantage of being able to dry materials down to a moisture content corresponding to 10% relative humidity at temperatures down to 0°C.

Present research indicates that some species previously considered recalcitrant can be dried at 15°C and 15% relative humidity.

In gene banks for long term storage of seed drying is also done at 15°C and 15% relative humidity since this is considered a very gentle drying scheme. Chemical sorption drying is about the only solution to creating this climate.

---

3 CMC Automation, Skippershovedvej 10, DK-8585 Glesborg, Denmark.
Int. Telefax: +45 86 381959.
Example 11:

If the drying cabinet described above was equipped with a cooling unit keeping the cabinet temperature at 15°C, and if the drying air entering the sorption drier had 15% relative humidity, experience shows that the drying air would typically leave the sorption drier at 25°C with approx. 1% relative humidity, see Figure 20.

1) At 15°C, 15% relative humidity, the air contains
   1.6 g water/kg air and 19.1 kJ/kg air
2) At 25°C, 1% relative humidity, the air contains
   0.2 g water/kg air and 26.0 kJ/kg air

I.e. the drier has removed 1.4 g water and added 6.9 kJ per kg air.

Drying capacity would be:
1.4 g water/kg air * 1.2 kg air/m³ * 120 m³/hour = 200 g water/hour.

Necessary cooling capacity would be
6.9 kJ/kg air * 1.2 kg air/m³ * 120 m³/hour = 994 kJ/hour
994 kJ/hour / 3600 sec/hour = 276 J/sec = 276 W.

---

**Figure 20.** See example 11 for explanation.
5.6.3 Vacuum drying

The last possibility for creating low relative humidity at low temperatures is vacuum drying.

Example 12:
If in a vacuum oven with seed at atmospheric pressure the relative humidity is 100%, and the pressure is lowered to e.g. 1/10 (10%) of the original pressure, then the partial vapour pressure of water will also be 10% of the original.
In other words the seed in the oven will come to rest at a moisture content corresponding to 10% relative humidity instead of 100% relative humidity if the oven is kept at 101.3 millibar (mb) instead of 1013 mb.

For practical purposes the evaporation of water from the seed will always saturate the oven atmosphere to 100% relative humidity so the pressure in the oven should be the same percentage of the atmospheric pressure as the equilibrium relative humidity you want to reach.

An advantage of vacuum drying is that the temperature can be controlled. The temperature can be lowered by evaporating water from a spray nozzle inside the vacuum oven and be raised by heating the outside of the oven.

There is at present no commercially available vacuum plants with a size suitable for forest seed centres.

The effects of vacuum drying on the seed has not been thoroughly investigated. However vacuum drying has been used as a routine for large amounts of malting barley.

![Diagram of a vacuum oven](image)

**Figure 21.** Example of a vacuum oven.
### 6. SELECTED REFERENCES

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Seed Extraction, 1. The Tarpaulin Method of Sun Drying Cones and Seed Extraction. DFSC Technical Note No. 9.</td>
</tr>
<tr>
<td>Roberts, E.H. Ellis, R.H.</td>
<td>Water and seed survival Annals of Botany 63: 39-52</td>
</tr>
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</table>

APPENDIX 1

I-X diagram for humid air at atmospheric pressure = 1013 mbar.

The weight of dry air (Y) per cubic meter at temperatures (X) and dew points (C):

<table>
<thead>
<tr>
<th>X (°C)</th>
<th>Y (kg/m³)</th>
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<tr>
<td>-10</td>
<td>1.342</td>
</tr>
<tr>
<td>0</td>
<td>1.289</td>
</tr>
<tr>
<td>20</td>
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<td>1.128</td>
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<td>60</td>
<td>1.083</td>
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</tbody>
</table>
SORPTION ISOTHERMS

Moisture content (% wet weight) in equilibrium with relative humidities (extracted from Roberts 1972).

% Moisture Content

Carbohydrate and protein rich seed, desorption, low temperature.

Wheat 2% oil content:
- - - - desorption, 25°C
- - - - - desorption, 35°C
- - - - - - absorption, 35°C

Seeds with a high oil content, absorption, high temperature.

Note:

Desorption curves generally lie 1-2% higher in moisture content than absorption curves.

A 10°C rise in temperature will lower the curves with approximately 1% moisture content.