1 The Technology of Malting

Malting refers to the germination of cereal grains under artificially created or controlled conditions.

The process of germination results in green malt, which must be dried; for this reason, germination is followed by kilning. Once this has been accomplished, the final product is referred to as kilned malt.

The primary purpose of the malting process is to produce enzymes in the kernels. During germination, these enzymes bring about certain transformations in the substances stored as reserves in the grain. The formation of enzymes and their effects during germination should occur only to the extent necessary to carry out the desired function. Too much or too little enzyme activity will have a negative impact on the quality of the final product.

1.1 Malting Barley

A number of different cereal grains can be employed to produce malt (refer to Section 1.9); however, two-rowed barley is best suited for this process if the kernels have undergone consistent growth and uniform development. Barley with multiple rows, the original form of the grain, is not utilized for malt production in Europe to any great extent due to the weak, asymmetrical formation of the lateral spikelets (less space to develop on the ear means they are thin and crooked). Outside of Europe, however, this kind of barley is used in malt production due to its higher protein content and greater enzymatic power, facilitating the use of large quantities of adjuncts in brewing.

Two-rowed barley is divided into two main groups:

1. *Upright barley*: the spike is dense, wide, and usually stands erect while it is maturing; the individual kernels are arranged, so that they are close together (*Hordeum vulgare* ssp. *distichum erectum*).
2. *Nodding barley*: the spike is long, narrow, and bends, so that the ear hangs during maturation. The kernels are spaced further apart (*H. vulgare* ssp. *distichum nutans*).

Several varieties of nodding barley have found use as malting barley. These are primarily planted and cultivated as spring barley. The characteristics of the barley remain quite stable if breeding efforts focus on creating highly productive varieties that are adapted to the cultivation and harvest conditions of either a Continental European or a maritime climate. Additionally, these barley varieties are bred for enhanced resistance to plant diseases (mildew, barley rust, net blotch, etc.) in order to reduce the number of pesticide applications.

Some varieties of two-rowed winter barley have attained a qualitatively high level due to recent efforts in breeding, although how widely they will be available around the world in the coming years will ultimately be determined in part by policy decisions concerning malting barley. Breeding naked barley has not yet become established. This is also the case for procyanidin-free barley (refer to Section 1.1.2.6), for varieties with low lipoxygenase activity, and barley with thin cell walls, i.e., varieties with a lower β-glucan content (refer to Section 1.1.2.2). The quality of these barley varieties suffers under unfavorable climatic conditions, and they exhibit severe losses in yield compared to normal malting barley varieties.

A single mature kernel of barley can be classified as belonging to one of the two main groups based on the shape of the base of the kernel as well as the shape of the rachilla and the type of hair covering it. In addition to these characteristics, the shape of the lodicules and the spiculation of the inner lateral spinal nerves can be used for varietal identification.

Electrophoresis is one method offering a greater degree of certainty for identification through separation of the prolamin fraction (refer to Section 1.1.2.8). Immunological analysis is also possible. Recently, polymerase chain reaction (PCR) has been conducted in two stages for distinguishing barley varieties and has proven useful for this purpose as well. The advantage of analyzing the DNA in this manner is that the determination is not undermined by the malting process as is the case with electrophoretic methods when the malt is overmodified.

Malting barley is commercially classified and traded according to its provenance and variety. Depending on the climatic conditions and the characteristics of each individual variety, there may be substantial differences in the degree to which a particular variety can be malted and in its

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value as a brewing grain. For this reason, blending should be avoided.

1.1.1 The Morphology of Barley

The *barley kernel*, which is the fruit of the plant, can be described morphologically as follows:

1.1.1.1 The Embryo The *embryo* is the living part of the seed and is situated at the proximal end of the kernel on the dorsal side. It consists of the following structures: the shoot apical meristem (future stalk), cotyledon (seed leaf), and radicles (future roots). Merged with the embryo is the scutellum, which is also affixed to the endosperm and channels nutrients to the growing embryo from there. This function is performed primarily by the scutellar epithelium with its tube-like cells facing the endosperm.

1.1.1.2 The Endosperm The *endosperm* chiefly consists of two layers of tissue: those containing starch and those containing fat.

The core of the endosperm is made up of cells containing starch embedded in a framework of protein and gum substances.

The cells containing starch are surrounded by a triple layer of rectangular, thick-walled cells known as the aleurone or subaleurone layer. It is composed of proteins and fats. The layer close to the embryo is only one cell thick. A thin layer of empty compressed cells, the depleted endosperm layer, lies between the starchy tissue of the endosperm and the embryo. The contents of the cells in this layer have already been consumed by the embryo.

All biological and chemical changes in the barley kernel take place in the endosperm. As the plantlet develops, the endosperm is broken down to its constituent parts and utilized. Consumption of the endosperm during malting should be kept to a minimum for economic reasons. In this respect, the formation of enzymes and the degradation of structural and support substances take on a singular importance.

1.1.1.3 Tissues Surrounding the Kernel *The tissues surrounding the kernel*: the husks protect the kernel, which houses the developing plantlet, and consist of the inner husk on the ventral side, the palea, and the outer husk covering the dorsal side, the lemma. Under the husks, barley kernels possess two fused layers, an ovary wall or pericarp, and an inner wall, the seed coat or testa. Both are composed of multiple layers of cells that appear to be fused. The testa is semi-permeable, e.g., water can penetrate the membrane while higher molecular weight substances are retained. In addition, water brings various ions to the interior of the kernel.

1.1.2 The Chemical Composition of Barley

Barley consists of dry matter (80–88%) and water (12–20%). The dry matter contains organic compounds, with and without nitrogen, as well as inorganic components (ash).

1.1.2.1 Starch Carbohydrates, especially starch, are the main component of nitrogen-free organic compounds. Barley contains 60–65% starch (calculated as dry matter). With the help of chlorophyll, CO_2 and H_2O are ultimately converted to starch under the influence of sunlight, releasing oxygen in the process.

The reason that barley kernels accumulate starch is to create a store of nutrients for the plantlet, which can later be utilized in the early phases of its development. The starch is deposited as granules. They occur in two forms: the large granules are lens-shaped, while the small ones are more spherical. The latter increase with the protein content of the barley, and they are richer in minerals compared to the larger starch granules.

A starch granule consists of two structurally different carbohydrates, amylose and amylopectin. Amylose (normal or *n*-amylose) makes up 17–24% of the starch. It is usually located inside of the starch granule and consists of long, unbranched chains wound into a spiral configuration. *Amylose* chains are composed of 60–2000 glucose residues connected through α-1→4 bonds (maltose bonds). The length of the molecules varies with the molecular weight ranging from 10,000 to 500,000 Da. Amylose turns pure blue with iodine; it dissolves to create a colloidal suspension in water and does not form a gel. Enzymatic degradation of amylose, e.g., by α-amylase and β-amylase, results in the formation of the disaccharide maltose.

Amylopectin (iso-amylose or i-amylose) accounts for about 76–83% of the starch. In contrast to amylose, it consists of branched chains of molecules, which in addition to the predominant α-1→4 bonds, amylopectin also possesses α-1→6 bonds (at a ratio of about 15 to 1). The amylopectin chain branches at approximately every 15 glucose units, on average. This three-dimensional, branched structure is what determines the gelatinization capacity of amylopectin. Encompassing 6000–40,000 glucose residues, the molecular weight of amylopectin ranges from 1 to 6 million Da. Amylopectin also contains about 0.23%

phosphoric acid incorporated in ester-like bonds. The aqueous solution turns violet to pure red in the presence of iodine.

Starch is tasteless and odorless with a specific gravity of 1.63 g/cm^3 in the anhydrous form. Its energy of combustion is 17,130 kJ/kg (4140 kcal/kg), and the molecule exhibits a specific optical rotation value of 201–204.

1.1.2.2 Non-starch Polysaccharides In addition to starch, 10–14% of the barley kernel is made up of *non-starch polysaccharides*. For example, *cellulose* is found in husks where it serves as structural support, but it is absent in the endosperm. Like starch, cellulose consists of glucose residues; however, cellulose is linked glycosidically through β-1→4 bonds. Cellulose is tasteless and odorless, insoluble in water, and difficult to degrade either chemically or enzymatically. It does not play a role in plant metabolism and remains in the region of the kernel where it was formed. The cellulose leaves the malthouse unchanged, first serving a function in brewing as part of the filter (grain bed) during lautering. Analytically, cellulose is measured as crude fiber, comprising 3.5–7% of barley, expressed as dry matter.

The *hemicelluloses* are part of the structure of cell walls and aid in maintaining their strength. The type of hemicellulose found in the husks is made up of an abundance of pentosans, low amounts of β-glucan, and small amounts of uronic acids. These hemicelluloses have a low viscosity in an alkaline solution. During germination, the "husk" hemicelluloses remain virtually unchanged. By contrast, as structural components, the "endosperm" hemicelluloses possess a high specific viscosity. This type is high in β-glucan, low in pentosans, and contain no uronic acids. It is composed of glucose residues linked with β-1→4 bonds (70%) and β-1→3 bonds (30%). If degradation is incomplete, then the disaccharides cellobiose and laminaribiose are present. The pentosans consist of xylose units linked by β-1→4 bonds to which side chains of the husk pentosans, xylose, arabinose, and uronic acids are attached with β-1→3 and β-1→2 bonds. The endosperm pentosans consist solely of arabinose molecules linked with β-1→3 or β-1→2 bonds. The pentosan chains in the cell walls of the endosperm contain ferulic acid, which is bound to arabinose by an ester bond. Cross-linking occurs between the two ferulic acid molecules on the arabinose side chains as well as between the amino acid tyrosine and the pentosans and proteins. Hemicelluloses are linked to proteins with ester bonds, which causes these complexes to be insoluble in water. Their molecular weight can reach up to 40×10^6 Da. They can be converted into a soluble form through treatment with a dilute sodium hydroxide solution or through the action of enzymes.

The content of hemicelluloses and gum substances (non-starch polysaccharides) in barley depends on the variety and where it is grown (climate).

Gum substances are water-soluble hemicelluloses of a high viscosity. They consist of β-glucan and pentosan and form colloidal solutions in water. Their molecular weight is approximately 400,000 Da. The content of water-soluble gum substances can vary over a considerable range, but it is normally around 2%.

Lignin is a substance embedded in the cell walls of the husks.

1.1.2.3 Lower Molecular Weight Carbohydrates The *lower molecular weight carbohydrates* in barley include 1–2% sucrose, 0.3–0.5% raffinose, and 0.1% each of maltose, glucose, and fructose.

1.1.2.4 Lipids *Lipids* (fats) make up 2.2–2.5% of the dry matter found in barley. They are present in small quantities in the husks and in the endosperm, while 60% are located in the aleurone layer and about 30% in the embryo. Barley lipids are composed primarily of approximately 70% neutral lipids, the majority of which are triglycerides, along with around 10% glycolipids and 20% phospholipids. The triglycerides may contain up to three different fatty acids, which each form an ester with the glycerin. Thus, the number of potential triglyceride combinations is very substantial. They are partially consumed as the embryo grows, supporting respiratory metabolism and the formation of cells in the acrospire and rootlet.

1.1.2.5 Organic Compounds Containing Phosphoric Acid *Organic compounds containing phosphoric acid* supply the majority of the acidic compounds (primary phosphates) and buffer substances during germination. One example is phytin, an ester of phosphoric acid and inositol, a cyclic sugar, which is present as a calcium/magnesium salt in the husk. Compounds containing phosphoric acid play a role in maintaining the proper acidity level during germination.

1.1.2.6 Polyphenols *Polyphenols* or tannins are found in barley husks and in the endosperm. Although they only comprise 0.1–0.3% of the dry matter, through the precipitation of proteins, they influence the color and flavor of beer, not to

mention its stability and shelf life. The phenolic group of substances comprise simple phenolic acids, which are present in their free form, bound as glycosides or as more complex polyphenols. Proanthocyanins (anthocyanogens), catechins, and flavones represent different types of polyphenols, the polymerization and oxidation of which lead to higher molecular weight compounds. They can deepen the color and precipitate substances inherent to malt, wort, and beer. Polyphenols are considered reducing substances due to their capacity to be oxidized. The "tannoids," as they are known, also belong to the group of polyphenols and can be determined analytically. They have a molecular weight of 600–3000 (2–10 flavan rings) and are characterized by a protein-precipitating effect, along with strong reducing properties. The quantity of phenolic substances in barley depends on the variety as well as the growing conditions. Compared to continental barley, maritime barley contains a higher concentration of polyphenols on average, especially more tannoids. Carlsberg laboratories used genetic mutants to develop a special kind of barley which is unable to synthesize catechins and procyanidins (anthocyanogens) as it grows. Wort and beer produced with this barley contain only around 12% of the normal anthocyanogen content and therefore possess a much better physico-chemical stability than beers brewed with conventional malts.

1.1.2.7 Bitter Substances in Barley *Bitter substances in barley* belong to a class of substances known as lipoids. They exhibit an antiseptic effect and are characterized by a harsh bitterness. These bitter substances are found primarily in the husks and are readily soluble in water containing bicarbonate.

1.1.2.8 Proteins In general, *proteins* are an essential part of biological processes. Despite their occurrence in relatively small quantities, they nevertheless play a significant part in every step of beer production. An elemental analysis of key proteins yields the following limit values: C = 50–52%, H = 6.8–7.7%, N = 15–18% (average 16%), S = 0.5–2.0%, and P = 0–1%. The average nitrogen content of the proteinaceous substances is about 16%. Once the nitrogen content has been determined according to the Kjeldahl analysis, the value is multiplied by 6.25 to obtain the crude protein content of the barley.

The protein content (calculated as dry matter) ranges from 8–13.5% (1.30–2.15% nitrogen), normally between 9.0% and 11.5% (1.45–1.85% N). Barley with a lesser protein content is generally considered to be more suitable for brewing and is indispensable for producing light-colored malts and beers. Barley lacking in protein can result in wort deficient in the proteins necessary for foam formation and a full-bodied character in the finished beer. Furthermore, the wort may also lack the amino acids important for yeast nutrition. Protein-rich barley (over 11.5% protein) is more difficult to process in the malthouse. It also has a lower starch content and will result in a darker beer color with a fuller flavor, but one that sometimes can be perceived as harsh. Dark beers, on the other hand, require malt produced from barley with a higher protein content.

The protein content of the barley kernel depends mainly on the soil composition, crop rotation, fertilizer application, and weather conditions. The length of the growing period between sowing and harvesting is of particular importance. Protein is found in the material surrounding the kernel, in the endosperm and in the embryo.

Proteinaceous substances are stored in the endosperm in three localized places:

1. in the aleurone layer as gluten
2. under the adhesive layer along the outer edge of the endosperm as storage protein
3. in the starchy endosperm itself as histological or tissue protein.

Gluten extends beneath the pericarp and testa. Gluten is partially degraded during the germination process, while the remainder stays behind in the spent grain.

The variability in the protein content of barley is attributable to the *reserve protein*. As germination commences, the enzymes degrade the reserve protein first. The reserve protein supplies the majority of the water-soluble proteins.

The *histological protein* is enmeshed in the membranes of the endosperm cells and, along with other substances, plays a role in the cohesion of the cells. The more histological protein is present, the more difficult it is to degrade the cell walls.

Proteins are formed from amino acid residues. These are each linked by a peptide bond, which is a bond between the carboxyl group of an amino acid and the amino group of a second amino acid. Of the 130 amino acids known to date, 18–20 are primarily involved in the synthesis of plant proteins. Dipeptides are formed when two amino acids bond, and tripeptides from three amino acids. Oligopeptides consist of 3–10 amino acids, polypeptides of 10–100, and macropeptides of more than 100 amino acids. The sequence (order) of amino acids organized in a polypeptide chain is called the

primary structure. The spiral helices or folded sheets stabilized by hydrogen bridges are referred to as the secondary structure. Their arrangement in loops or coils is known as the tertiary structure. Where the secondary structure ends, and the tertiary structure begins, is often difficult to distinguish. In addition to the peptide bond, the tertiary structures feature hydrogen bonds as well as strong disulfide bonds, which, along with electrostatic interactions and hydrophobic bonds, are responsible for the characteristic structure of proteins. The quaternary structure is formed by assembling several tertiary groups with no covalent bonds (e.g., disulfide bridges).

The barley kernel contains the following protein fractions: albumins (soluble in distilled water), globulins (soluble in dilute salt solutions), prolamins (soluble in 50–90% alcohol), and glutelins (soluble in alkaline media). Each of these protein groups can be subdivided using electrophoresis into 7–15 different fractions or even more in some cases. Their molecular weight ranges from 10,000 Da to several million. While albumins and globulins are located in the starchy endosperm, reserve proteins are primarily made up of prolamins and glutelins.

The albumins also include protein Z, which can also bind β-amylase. In beer, it is responsible for colloidal haze as well as foam. Its molecular weight is 40,000 Da. The albumins also include the lipid transfer proteins LTP 1 and LTP 2. As with protein Z, they undergo little modification during malting and brewing. They contribute to beer foam and also to colloidal turbidity. Furthermore, they also may play a role in the gushing phenomenon (spontaneous foaming over) of beer.

The barley kernel also contains other proteinaceous substances as well as small amounts of nitrogenous compounds of low to medium molecular weight. These compounds result from the interrupted formation of true proteins, halted at an intermediate stage of development as the barley kernel matures, or they are products of the physiological degradation of higher molecular weight proteins.

Classification of the proteins and their degradation products is based on their distinctive chemical and physical properties, their occurrence, their varying degrees of accessibility to enzymes, and their physiological functions.

The protein bodies are colloids; they do not diffuse through membranes due to their size. They are hydrated, and like their constituent amino acids, they are amphoteric. Depending on the prevailing pH, excess negative or positive charges are present. At the isoelectric point, the protein is electroneutral. The protein can be denatured by altering the environmental conditions, e.g., through the application of heat, the addition of reagents that extract water, and a shift nearer to the isoelectric point. Denaturation is a structural change in a protein which brings about the loss of its biological properties (e.g., enzymatic activity). It can be reversible or irreversible, depending on the conformation that results. Denaturation is irreversible if the peptide chains of covalent bonds (e.g., disulfide bonds) are unfolded. Macroscopic flakes are formed as denatured particles are moved or enriched at interfaces (e.g., gas/liquid), where they combine as "break" material. This process is called coagulation.

During germination, proteolytic enzymes cleave high molecular weight proteins, creating simpler compounds such as amino acids. Protein degradation, which occurs during malting, also continues during mashing.

1.1.2.9 Enzymes *Enzymes* are complex organic substances, which are of great importance for all biological processes and thus also for the germination of the barley kernels. They have the ability to degrade organic substances of a high molecular weight without being consumed in the process. Most enzymes consist of a protein constituent (apoenzyme) and a non-proteinaceous constituent (prosthetic group or coenzyme). The apoenzyme determines the substrate specificity, while the prosthetic group or the coenzyme serves as the reactive region. Simple enzymes, such as hydrolases, consist exclusively of protein. In these enzymes, the reactive region is made up of functional groups of different amino acids. A certain steric arrangement must be present in the overall complex for the enzyme to have the desired effect on a specific substrate. The enzyme interacts with the substrate to be degraded through an exchange of electrons, releasing the cleavage product and the unmodified enzyme that continues to react with additional substrate. The effect of the enzymes is largely dependent on environmental influences, the most important being temperature and reactivity of the substrate. The enzymes are promoted by activators and inhibited by inhibitors.

Enzymes are only active within a specific *range of temperatures*. Every enzyme functions in an optimal manner at a certain temperature. As the substrate is heated above this optimum temperature, the enzyme increasingly loses its effectiveness. Most enzymes can only tolerate temperatures between 60 and 80 °C.

The reactivity of the substrate and its pH influence the dissociation of enzymes and their degree of hydration. Every enzyme functions most favorably at a certain acidity or optimal pH at which its activity reaches a maximum. The optimum pH can shift with changes in the temperature of the substrate. It is at their pH optimum that enzymes are usually the most resistant to heat.

The progression of the reaction is influenced by the concentration of the enzymes as well as the concentration of the substrate.

Heavy metals, such as copper and tin, as well as oxidizing agents, colloid-modifying substances, and the like have an *inhibiting effect* on enzyme activity. Alcohol, ethers, and formaldehyde are damaging to enzymes in higher concentrations, especially at high temperatures. Enzyme *activators* include acids, neutral salts, colloids, and other substances that either bind to or activate the enzyme. Substances can also serve as activators if they free the enzyme from inhibitors, e.g., proteins adhering to their surface.

A group of enzymes occur in soluble form (lyo enzymes), while others are released from their protoplasmic bonds over the course of a degradation process, through which they are rendered effective (desmo enzymes).

The quantity of active enzymes initially present in the barley kernel is low. After the existing soluble nutrients in the endosperm have been consumed, enzyme formation is induced to meet the nutritional needs of the embryo during germination. Furthermore, enzymes that are present, yet still inactive, are activated (e.g., β-amylase and some proteases through SH groups); however, the majority of the enzymes are produced by secretion of a substance similar to gibberellin, a growth hormone that induces the development of cell wall-degrading glucanases (hemicellulases), α-amylase, endopeptidase, and acid phosphatase in the aleurone layer.

In addition to these hydrolytic enzymes, oxidases such as catalase, peroxidases, polyphenol oxidases, and lipoxygenases I and II as well as superoxide mutase also play a role. They are also present, in part, in the dormant kernel in an active form, or they are formed or activated during germination.

The enzymes of the respiratory complex are important for the advancing metabolic processes.

The distribution of the enzymes is not uniform. The largest concentration is in the dormant grain near the embryo. The process of identifying and classifying enzymes is based on their effect on specific substrates.

1.1.2.10 Inorganic Constituents The *inorganic constituents* of barley are incombustible and remain as ash after combustion. Their total amount calculated and expressed as dry matter is 2.4–3% and consists predominantly of potassium phosphates (56%) and silica (approximately 26% as SiO_2). Inorganic constituents play an important role in maintaining acidity as chemical buffers during germination and mashing, during fermentation, and in the finished beer, which is largely attributable to the action of the acidic primary phosphates. These inorganic constituents provide essential nutrients for the embryo and the yeast.

1.1.2.11 Moisture Content The *moisture content* of barley can vary between 12% and 20%. Barley from warmer climates with low amounts of precipitation may exhibit a moisture content of 12–14%, while that cultivated in wetter climates can have a moisture content of 16–18% or even in excess of 20%. The moisture content varies with the weather conditions from year to year, with the harvesting method, and according to how the barley is treated after the harvest. A high moisture content is disadvantageous from an economic standpoint because the barley contains less dry matter. Moist barley is not stable in storage and possesses a low germinative energy and a high water sensitivity. It is also slow in overcoming dormancy. Storing undried barley is difficult since it is very susceptible to warming, prone to mold growth, and, as a result, may develop an undesirable odor and experience subsequent problems with germinative capacity. Moist barley requires constant temperature monitoring and frequent redistribution in storage. It is more difficult to malt and produces a less-uniform product and likewise sustains higher losses than barley with a lower moisture content.

1.1.3 Determining and Evaluating the Properties of Barley

An important prerequisite for properly assessing malting barley is the collection of a truly representative sample. The grain sampling spear developed by Barth, referred to as "Barth's sampler," allows samples to be collected from various areas of a bag or bulk shipments of barley. Automatic sampling devices are advantageous when larger quantities of bulk barley are delivered, or when the barley is transferred from silo to silo. The sample should be kept in well-sealed containers (to maintain the moisture content); however, it is not recommended that samples be stored in sealed containers over a longer period.

1.1.3.1 External Features of the Barley Kernel

External features

(a) *Appearance*: lustrous, indicating that the barley was allowed to mature and was harvested under dry conditions; the moisture content is usually low.

(b) *Color*: uniform, light yellow; kernels that are not quite mature are greenish in color. Kernels subjected to rain and completely mature kernels both exhibit brownish or brown tips. Gray kernels or those exhibiting red or black spots have been infected by microorganisms. Frequently, fungal mycelium infiltrates the endosperm of the kernel. Barley kernels that are extremely pale (white) are often hard and glassy.

(c) *Odor*: pure and straw-like; kernels that have been rained upon, those with a high moisture content, or those stored under poor conditions have a musty, moldy odor.

(d) *Husk character*: as thin as possible and wrinkled; the smaller the husk fraction is (7–9%), the finer and milder the quality of the barley is. Fine, transverse wrinkling is a sign of high extract content, low protein, and low moisture. A higher husk content (11–13%) is undesirable for pale, high-quality beers. Winter barley usually has 0.5–1% more husks than comparable spring barley. Six-rowed barley often contains an even higher proportion of husks.

(e) *Purity*: the barley should be free of foreign cereals, extraneous seeds, plant and animal pests, and damaged or pre-germinated kernels. *Pre-germination* (kernels that germinated on the plant in the field prior to the harvest) can be recognized by the dried rootlets on the kernels ("open" or visible pre-germination). However, as these are often dislodged and separated from the kernels during transportation, it is recommended that the barley be examined for the presence of "hidden pre-germination," e.g., to determine if acrospire growth has occurred that is not yet visible. This can be determined visually, e.g., by steeping in boiling water, through copper sulfate, and through the determination of lipase activity. The majority of these kernels will have lost their ability to germinate. Excessive acrospire growth may be apparent. In some instances, the kernels may already be friable, allowing water to penetrate the kernels unhindered during steeping. During germination, abnormal metabolism may be observed, indicated by an odor uncharacteristic of germinating malt; mold formation also increases (resulting in a greater tendency for the beer to gush when poured). Barley with more than 4% pre-germinated kernels should be rejected.

Cracked grains can result from exposure to rainfall during the later stages of maturation. They are split longitudinally along the kernel; the endosperm is exposed, and strong microbial growth is readily evident during storage as well as during steeping and germination. This is also accompanied by the risk of excessive moisture uptake. For this reason, barley lots with more than 3% cracked grains are to be rejected.

Incomplete lateral husk closure occurs when the lemma (dorsal husk) does not entirely cover the palea (ventral husk). Even if the endosperm is undamaged, this is nevertheless considered to be another kind of kernel anomaly. Furthermore, damage to the husk which is not attributable to awn removal may be present. Secondary growth occurs when the barley plant creates an additional set of kernels due to the prevailing weather conditions. These kernels are not fully developed; they often do not mature completely and therefore exhibit poorly formed kernels (apparent during sorting or grading). Due to the short vegetative growth period, the kernels are low in enzymes.

If multiple deficiencies are present, the barley should not contain more than 5% abnormal kernels in total, in order to be considered of a sufficient quality for malting.

Mold growth by *Fusarium* species results in a discoloration on the surface of the kernel; however, these "field molds" may already have formed a mycelium in the endosperm. Molds commonly found in storage silos such as *Mucor*, *Rhizopus*, and *Alternaria* species are visible as a black film. Mold-infested barley has a musty odor. The germinative capacity of these kernels may have already suffered as a result of unsuitable storage conditions (moisture content and temperature). These findings give rise to further analyses, e.g., the determination of relevant red kernels (from *Fusarium* species, a maximum of five infected kernels per 200 g or 1%) and finally the gushing test (refer to Sections 1.9.1.4 and 7.6.8). Furthermore, any barley infested with insect pests, such as grain beetles, must be rejected.

(f) *Uniformity*: mixing two or more barley varieties, barley from different regions or crop years is detrimental to achieving a uniform

malting process. Likewise, mixing barley with different protein levels or from dried and undried lots is prohibited. The purity of the variety can be determined on the basis of morphological characteristics (base of the kernel, rachilla, lodicule, and spiculation of the lateral nerves), while the latter factors can be detected to some extent by determining the capacity for water uptake, kernel hardness, and water sensitivity. An electrophoretic separation of the prolamin fraction provides a reasonable basis for varietal identification.

1.1.3.2 Physical Examination of the Barley Kernel *Physical examination*

a. *Size and uniformity of the kernels*: the plumper the barley kernel, the higher its starch and extract content are and thus its value for brewing. A high moisture content in barley can often make it appear to be plump. The size and uniformity of a barley is determined by a sieving test with three sieves of 2.8, 2.5, and 2.2 mm slot widths. At least 85% of the barley kernels are retained on the first two sieves in uniform barley samples. The higher the proportion of kernels larger than 2.8 mm, the higher the extract content is in malt produced from this barley.
b. *Endosperm character*: the endosperm may be friable as well as more or less glassy. Barley can be steeped briefly in water and gently dried to determine whether glassiness is permanent or only temporary. The character of the endosperm can be tested using grain testers or grain cutters (farinatome). The friabilimeter developed by Chapon may also be used to determine the friability of barley kernels. Classifying kernels into categories according to their hardness allows insight into the homogeneity of a barley sample.

The diaphanoscope allows the direct evaluation of the condition of the endosperm by illuminating the kernels. Glassy kernels are permeable to light rays, while friable kernels appear dark.

A white, friable endosperm is preferable to a glassy, oily one. Extremely dry, hot weather conditions during barley maturation and harvest as well as poor soil quality are often the causes of glassiness.

c. The *hectoliter weight* of barley ranges from 66–75 kg. For malting barley, 68–72 kg is standard, rarely more. Heavy barley is preferable for malting applications.
d. The *thousand kernel weight* of air-dried barley is between 35 and 48 g, while that of anhydrous barley ranges from 30 to 42 g. One thousand kernels of air-dried barley weighing 37–40 g is considered to be light, 40–44 g to be medium heavy, and 45 g is heavy. Heavy barley is more desirable for malting.
e. *Germinative capacity*: chemical methods (e.g., application of hydrogen peroxide, dinitrobenzene, or tetrazolium) are used to determine the number of viable kernels. This figure must not be lower than 96%. Germination is the most important characteristic for malting barley. Kernels that fail to germinate may be non-viable or dormant and are referred to as "lie-backs." These kernels will never become malt but instead will remain unmalted grain.
f. *Germinative energy*: this indicates how many kernels will actually germinate within a certain period of time, e.g., after 3 or 5 days. As a measure of maturity and the germinative potential of a barley sample, it should be as close as possible to the value for germinative capacity.
g. *Germination index*: this value provides an overview of how uniformly germination progresses. It is usually performed for the same period as the analysis for germinative capacity (5 days) in Petri dishes containing 100 kernels and 4 ml of water. The germinating grains are counted and removed after 24, 48, 72 h, and so on. A uniform germination process results in a germination index of around 8, whereas barley with poor, irregular germination has an index close to 5.
h. *Water sensitivity*: based on the Pollock test (a steeping test of 100 kernels, in 4 and 8 ml of water, respectively), this analysis provides information on the sensitivity of barley to excessive contact with water when steeping. It is heavily dependent on the particular stage of kernel maturity and is therefore also linked to the weather conditions during the ripening and harvesting of barley. The difference between the kernels germinating in the 4 and 8 ml sample after 120 h is evaluated as follows: up to 10% as very low sensitivity, 10–25% as low sensitivity, 26–45% as satisfactory, and over 45% as very sensitive to water. However, this analysis result is only of significance if the maximum germinative energy has been reached.
i. *Water uptake capacity* according to Hartong–Kretschmer: this method assesses the capacity of a barley to absorb water, which is determined 72 h after performing a special steeping regimen. The water uptake capacity is primarily influenced by the degree of maturity, the

variety, and where the barley is grown. A value of 50% is considered to be very good, 47.5–50% good, 45–47.5% satisfactory, and less than 45% inadequate.

1.1.3.3 Chemical Analysis of the Barley Kernel

Chemical analysis of barley

(a) *Moisture content:* normally, barley kernels contain 15–16% moisture, 13–14% in dry years and 16–20% in wet years. A determination of the moisture content forms the basis for calculating dry matter in all chemical analyses for barley.
(b) The *protein content* of barley, expressed as dry matter, ranges from 8% to 13.5%, with average values between 9% and 11.5%. Higher levels of protein reduce the extract yield of malt and create difficulties in processing and modification. For pale beers, low-protein barley is necessary for the malt, whereas dark beers require more protein-rich barley.
(c) The *starch content* varies between 58% and 66%, expressed as dry matter.
(d) The *extract content* is a measure of all water-soluble compounds and is performed by means of an enzyme additive. Barley contains 72–80% extract, expressed as dry matter, and is therefore 14.75% higher on average than the starch content. This provides an approximation of the extract content found later in the malt; however, the extract does not reach this level. For this reason, micromalting is being conducted on barley samples with increasing frequency to determine the extract value of malt. Bishop's formula provided below can be used for general orientation:

$$E = A - 0.85P + 0.15G$$

A = a constant, P = protein content (d.m.), G = thousand kernel weight (d.m.)

Near-infrared transmission spectroscopy (NIT) represents one option for estimating the extract content of barley, especially when analyzing small sample quantities in the early stages of breeding. Calibration using wet chemistry methods is required for the use of routine analysis. Micromalting yields reliable values for extract content (refer to Section 1.9.5).

1.2 Preparing Barley for Malting

(Delivery, conveyance, cleaning, sorting, and storage of barley)

1.2.1 Receiving Barley in Bulk

Receiving should take place on a covered, draft-free ramp. Barley is predominantly transported as a bulk material. A number of spacious barley bunkers is necessary to facilitate the rapid unloading of the transport vehicle. At the very least, these bunkers should be able to accommodate the contents of a single transport unit (1–8 bunkers, each with the capacity to store 10–25 t of barley).

Monitoring the weight of the barley being delivered is an absolute necessity. This can be done using a weighbridge or an automatic scale built into the conveyor for transporting the delivered barley.

Collecting a representative sample with a sampling device is highly recommended for establishing the uniformity of the lot upon delivery. The decision to accept the lot of barley and to commence unloading is based on the values determined for the moisture content and germinative capacity. In some instances, the protein content may also be determined using a rapid method (NIT).

1.2.2 Conveyor Systems

Conveyors are used in malthouses to move barley, green malt, and kilned malt. Today, barley is transported solely as bulk material; thus, a distinction need only be made between mechanical and pneumatic conveyor systems.

In *mechanical systems*, horizontal and vertical transport occurs using various types of conveyors.

Horizontal conveyors include screw and trough chain conveyors as well as conveyor belts; less common are tube chain and drag flight conveyors as well as vibrating feeders.

Vertical conveyors for barley delivered in bulk consist almost exclusively of bucket elevators.

A combination of different conveyor systems allows the barley to be moved in any direction within the facility without the need for human labor. The mechanical equipment is highly effective (up to 100 t/h) and efficient. The energy consumption is generally low, especially when a combination of trough chain conveyors and bucket elevators is employed. The bulk material is transported in a very gentle manner.

In *pneumatic transport*, the material is moved by suction and compressed air through narrow tubes; the requisite air flow is generated by centrifugal fans, rotary positive displacement blowers, or piston pumps.

Suction is used to move the bulk barley from various points in the system to a central location,

and compressed air accomplishes the opposite. A combination of both suction and compressed air offers a wide range of options for conveying barley in bulk. The force required to move barley pneumatically is 10–12 times that of mechanical systems, so there is a risk that the barley can become damaged when transporting it at high velocity, especially around sharp curves in the system.

1.2.3 Cleaning and Sorting Barley

When it is delivered, the barley is still "raw barley" and has yet to become "malting barley." It must first be freed from other materials, which cannot be malted, and then sorted according to kernel size. The delivery of large amounts of barley to the malting facility within a short period of time makes it necessary to divide grain handling into a rough, preliminary cleaning step and a subsequent primary cleaning and sorting step. Pre-cleaning the barley upon delivery is essential if it is to be stored in silos.

The *barley cleaning equipment* must be installed in closed rooms due to the dust liberated by the movement of the grain as it is cleaned. The throughput of the preliminary cleaning equipment must be adapted to properly handle the quantities received on a daily basis. The same is true of the transport systems for conveying the incoming barley. However, the capacity of the equipment employed in the primary cleaning step must be equal to that necessary to handle the quantity of barley entering the steeping vessel in 1 day or over a weekend.

The *cleaning equipment* consists of several machines, each of which is designed to remove a certain type of impurity. In smaller malthouses, all cleaning operations are carried out by one machine, while larger facilities will have separate machines for each task. In the latter case, malt cleaning may be spread over several floors.

The following cleaning devices are common.

1.2.3.1 Pre-cleaning and Pre-sorting A *pre-cleaning machine* for coarse pre-cleaning and pre-sorting (aspirator). This consists of single or double grading screens with slot widths of 5.0×25 and 1.5×25 mm, which are kept in constant motion by an eccentric drive and an exhaust fan with suction chambers. Modern pre-cleaning machines feature oscillating screens that achieve a superior sieving performance through high-frequency vibration. Impurities sufficiently light in weight can be removed by means of air flowing up through an ascending air classifier. A flow rate of approximately 45 m^3/min is required for this type of air classifier with a capacity of 10 t/h.

The same task is fulfilled by *air separators*, in which the barley falls vertically through a shaft where it is met by a strong current of air entering from the side, perpendicular to the falling barley. The air is guided by a baffle plate, so that it only flows in a certain direction. Depending on their weight, heavier impurities and barley kernels as well as husks and straw are deflected by the air current to varying degrees and are thus separated from the barley kernels. The mix of material that forms on the margins is returned to the separator. The air is purified and then reused in the classifying process; 95% of the air is recirculated through the system.

1.2.3.2 Awns and Dirt A *de-awner*, which consists of a drum with paddles or blunt knives, cuts off the awns and also loosens any dirt adhering to the grain. The de-awner should be switched off if the barley is extremely dry or can easily be damaged. It is beneficial if the rotation rate of the de-awning device can be adjusted.

1.2.3.3 Ferrous Material A powerful magnetic device, usually an electromagnet in the form of a rotary drum, is employed to remove all ferrous metal.

1.2.3.4 Stones A *destoner* removes stones similar in size to barley kernels: the product is distributed over the breadth of an inclined screen in a thin layer. A stream of air passes through the layer, elevating the barley kernels and suspending them above the screen. Pieces of a defined density, such as stones and also shards of metal, settle out and are eliminated through the motion of the screen. These eventually migrate upward along the screen and are discharged from the machine. An air flow rate of 150 m^3/min is required to process 10 t/h of barley.

1.2.3.5 Trieur Cylinders A *trieur cylinder* is used to remove all impurities spherical in shape, namely seeds and half kernels. Indentations or pockets 6.5 mm in diameter have been pressed into the cylinder, which consists of a specially fabricated steel alloy sheet. As the cylinder rotates, spherical impurities are captured in these pockets and are held there until they near the apex of the rotating cylinder. There, they fall out of the indentations and are collected in a trough inside the cylinder

from which they are removed by means of a screw conveyor. At a circumferential velocity of 0.55 m/s, the gravitational force is still strong enough to outweigh the centrifugal force to the extent that the seeds and half kernels retained in the pockets are certain to fall into the collecting trough.

The more modern "Ultra-Trieur" is horizontal in design. The barley is uniformly transported by an impact roller, which is also tasked with distributing the flow of grain evenly across the surface of the cylinder to improve the sorting process. This design prevents the generation of the kidney-shaped circular flow patterns that typically emerge through the movement of bulk grain.

The *sharp edges of the pockets* in a trieur guarantee a clear, uniform separation of the material; however, they become worn over time due to the silica content of the husks. The movement of the *trieur drive* should be smooth and steady, not jerky. This is best accomplished by spur and bevel gears. The *size of the effective separation area* is relatively small; it can be increased through high circumferential speeds and the impact rollers described previously. *Correctly positioning the collecting trough* is essential for the trieur to function as intended without incurring problems. For barley that is lighter in weight, the trough must be adjusted to a higher position because the intact kernels remain in the pockets for a longer period. Conversely, heavy barley requires the trough to be set at a lower position. The *condition of the barley lot* also affects trieur performance: as the purity of the barley declines, the amount that can be processed per hour also decreases. In dry years, the proportion of half kernels in the raw barley will be higher, since drier kernels are more easily damaged during threshing. In addition, plump, squat barley grains are difficult to sort. Trieur performance is not only determined by the construction and dimensions of the machine, but it also depends on the steady and uniform intake of the material to be processed. The most suitable feed technique is over an adjustable metering or dosing device. The machine should not be operated while empty, and the system should not be overloaded.

The function of a high-performance trieur can be augmented with a similarly constructed but smaller *secondary trieur*. This machine is used to reclassify the material discharged from the primary trieur, enabling perfectly intact barley kernels to be salvaged. The pockets in the secondary trieur are generally 5.75 mm in diameter.

At 800 kg/(m^2·h), the throughput of the high-performance trieur is about four times greater than that of *less-modern trieurs* with cylinders consisting of zinc plates with milled depressions or pockets. The performance of less-modern trieurs was governed by the angle of its slight gradient (6–10%) and by its low peripheral speed of 0.3 m/s.

Monitoring the performance of the separation process involves examining the cleaned barley to determine whether impurities are still present and doing the same for the discharged material to establish whether intact barley kernels are among the dockage. The removal of the half kernels and seeds is usually done before sorting the barley.

1.2.3.6 Dust Removal Systems A *dust removal system*, consisting of a *fan*, eliminates dust and light impurities from the barley through the movement of the air it generates. *Dust collectors*, in turn, remove dust at the point of occurrence, if possible. Dust removal is necessary to avoid wear on machinery and to minimize the risk of combustion, explosion, and infection.

The simplest collectors of this kind are *dust chambers*. The dust-laden air is blown into these compartmentalized spaces, which reduce the speed of the air flow and allow the dust particles to settle as the air – not entirely devoid of dust – is discharged into the outdoors.

The "cyclone" *dust collection device* is constructed of sheet metal in the shape of a cylinder at the top and a conical vessel at the bottom. Air containing dust enters tangentially and is directed downward by the angle of the top of the cyclone. The circular movement caused by the tangential introduction of the air projects the particles outward through centrifugal force, where they spiral down along the wall of the chamber until they finally exit through an opening at the base, usually fitted with a rotating valve. The purified air rises vertically through the center of the cyclone and escapes. The cyclone is supplemented by downstream "centriclones" or centrifugal classifiers that operate in a similar manner. Arranged in batteries, these centrifugal classifiers remove fine dust particles from the air.

Dust filters also remove fine dust particles from air that is pulled or blown through textile sleeves. The shape of these filters makes it possible to house a large filtration area within a small space. A distinction is made between two different systems: *pressure filters* use pressure to move compressed air into *sleeves* from the top. As the air passes through the sleeves, the dust is retained on the interior walls, allowing the purified air to be released into the room. The surface of the filter material is freed of dust by a rake that moves up and down the filter.

Bag filters pull dust-laden air through a system of *sleeves* into a tightly sealed housing, and from there, the cleaned air is directed through the rest of the system by a fan. The dust particles are retained by the woven material of the bags arranged in multiple compartments of the same size. The surfaces of the filters are freed from the adhering dust automatically by either a mechanical or a pneumatic device. Suction filters are more effective at dust removal than pressure filters.

Not only must the individual machines used for grain cleaning be connected to the dust removal system but all of the conveyors, silo compartments, and the barley dryer as well. Dust-free operation can only be achieved by doing so. The performance of the dust removal equipment must therefore be adjusted to meet these requirements (quantities of air to be purified and the number of devices or machines to be attached and their capacities).

In Germany, for example, the maximum dust content of the air leaving the system is legally specified by the government (in the German regulation *Technische Anleitung zur Reinhaltung der Luft*). It may not exceed 50 mg/m^3 in general or 20 mg/m^3 in residential areas. Cyclones have the capacity to satisfy the former value, while the latter requires woven filters that can achieve a discharge rate of 10 mg/m^3.

The amount of dust generated usually amounts to approximately 0.02%.

1.2.3.7 Sorting Barley *Sorting* barley into different sizes or grades is necessary to achieve uniform steeping and germination conditions as well as to obtain a higher yield by separating out the smaller kernels. Sorting is carried out on slotted metal sheets or sieves. The metal sheets may be formed into cylinders capable of rotating on their axis (sorting cylinder), or they may be arranged above one another, connected by a vertical drive shaft, which is driven by eccentric mass causing the sieves to oscillate (plansifter).

Barley kernels that are larger than the width of the respective slots remain on the sieves, while smaller kernels fall through. The raw barley is usually sorted by size into three fractions using two different slot widths. Grade I barley is destined for malting; these kernels have a thickness of more than 2.5 mm. Grade II exhibits a kernel size of 2.2–2.5 mm. The waste, also referred to as screenings (less than 2.2 mm), contains thinner kernels that are not worth malting (feed barley).

The following aspects are essential in order to obtain an acceptable degree of sorting performance when separating barley into grades using a *sorting cylinder*:

Material, fabrication, and gauge of the sieves. Slots 25 mm in length are stamped into the steel sheet that serves as the cylinder. As the gauge of the metal (normally 1.0 mm) increases, the separation becomes more precise. Material wear over time caused by contact with the silica contained in the husks gradually widens the slots.

The barley must not flow over the sorting surface too rapidly. The *rate of flow* is determined by the circumferential velocity (0.7 m/s) of the cylinder and by the arrangement of battens mounted in the chamber, which cause the forward movement of the barley while at the same time allowing heavier loading of the sieves. Modern cylinders are horizontal, whereas previously the movement of the barley was accomplished by inclination of the cylinder (6–10%). The rotation must be uniform, which is why the device should be operated by a gear wheel or a spur wheel drive.

Throughput: the processing capacity depends on how the barley is conveyed through the machine; the stream of barley should be very uniform and not too deep. Only when the barley flows as a thin layer does each kernel reach the sorting surface. A throughput of 380–400 kg/(m^2·h) per grade can be fed into the machine.

The effective sorting area is only about 1/4 of the total circumference. It is reduced by kernels becoming lodged in the slots. In order to prevent this, special sweepers, e.g., wooden rollers and brushes, are used, which roll over the sorting cylinder as it rotates. To ensure the proper function of these sweepers, the cylinders must be perfectly round since even slight indentations affect the performance.

The *condition of the barley:* grain with few impurities or grain that has been pre-sorted can more readily be sorted than grain with a higher level of impurities. For this reason, barley lots being delivered to the malting facility should fulfill certain requirements regarding the degree of purity and uniformity.

Since the ratio of barley belonging to grades I and II can fluctuate dramatically, this raises the following question regarding the best strategy for the use of standardized slot widths for sorting barley: should other, more relevant, alternative dimensions be employed (e.g., 2.4 and 2.0–2.1 mm) rather than the current dimensions?

The plansifter is a twin system of flat screens arranged one above the other, which are set in a horizontal, oscillating motion by an eccentric mass mounted perpendicular to the vertical drive shaft. The grain is evenly distributed over the set of sieves. The arrangement of the slotted areas

alternates between those running crosswise and those arranged longitudinally. This design enhances the sorting performance. Each set of sieves consists of three sorting elements, a perforated metal sheet with a distribution plate, a spring-loaded sieve frame with rubber balls to keep the sieves free of blockage, and a metal catch tray. Once the grain to be sorted reaches the catch tray, it is routed to laterally arranged channels onto further sieve units. The throughput performance of plansifters is higher than that of cylinder separators, and they also occupy less space. A plansifter capable of processing 10 t/h requires approximately 3 kWh of electricity.

Newer plansifter designs feature annular or octagonal sieves. The plansifter consists of two or four screen discs mounted horizontally around a central axis. These are divided into eight interchangeable sieve segments. The grain is fed into the device from above, through the center column. The sieve movement is generated by an eccentric drive with a horizontal stroke of 80 mm in a circular direction. Radially arranged impact bars ensure a zigzag-like deflection of the kernels, which in addition to redistributing the material also enables more intensive processing. Rotating, spring-mounted brushes prevent the sieves from becoming blocked. The screen discs move in opposite directions, effectively balancing the weight and allowing the machine to operate smoothly.

Plansifters are capable of processing up to 12 t/h per unit. This can be increased by assembling several machines one above the other. The electrical power consumption for a unit capable of processing 12 t is 2 kWh. A new design with a capacity of up to 85 t/h per unit is based on a different concept: after being aspirated at the inlet, the grain passes through preliminary screen for the removal of coarser impurities. The material to be sorted is then directed onto 10 primary screens that are positioned at a slight incline. Their constant motion is maintained by an eccentric drive. The sorted grain is exposed to an adjustable stream of air as it enters the ascending sifter, where dust and fine particles are eliminated. The machine is available in two models: for separation into either two or three grades. In the former, grades I and II are classified together, while in the latter, grades I and II are separated from one another, however, with a reduction in throughput of about 30%. The processing speed is generally dependent on the sorting task, i.e., the quantity of malting barley in the lot to be separated and the degree of sorting accuracy. A device with 44 m^2 of sieving surface area can separate 40–85 t/h of barley into two grades, depending on the degree of sorting accuracy required, while a device with a 40 m^2 sieving surface area sorting into three grades can process 32–60 t/h of barley. The electricity required to operate the aspirator is 0.75 kW, and for the sieve drive, 3.0 kW.

In normal crop years, *the amount of dockage* ranges from 0.5% to –1.0%. This may increase to 4% under unfavorable conditions and may be as high as 10% in years with heavy precipitation. The proportion of grade II barley varies with climatic conditions. On average, it is around 10–15%.

Sorting accuracy is checked in the laboratory using milled sieves made of brass. A sample of 100 g of barley is shaken for 5 min in the device at a stroke of 18–22 mm and 300–320 revolutions/min.

Barley cleaning equipment requires constant monitoring and care.

1.2.4 Preparing and Storing Barley

It is the duty of the maltster to properly prepare and store barley, both for economic and technological reasons. This can be divided into two stages:

1. storage of freshly harvested barley until it has overcome dormancy and
2. storage of barley that is ready to undergo the malting process until it can be processed.

Freshly harvested barley almost always possesses a low germinative capacity. The highest level of germinative energy is required for malting, and this can only be achieved over the course of proper storage. Dormancy is nature's safeguard for preventing the untimely germination of kernels on the stalk, should adverse weather conditions occur during crop maturation and harvest.

During maturation of the barley on the stalk, low molecular weight substances are utilized to create high molecular weight reserve substances. Most enzymes show only minor activity once the barley reaches full maturity, i.e., when it is sufficiently ripe and ready to be harvested. This is attributable to a decrease in gibberellic acid, a compound that triggers enzyme induction, and thus germination, in mature barley. An accumulation of a germination-inhibiting compounds involved in inducing dormancy in barley, such as abscisic acid, blocks the formation of enzymes. Dormancy is broken in barley when the quantity of the abscisic acid decreases and the gibberellins increase over the course of post-harvest maturation, or the barley is subjected to certain processes for doing so. Only after dormancy has been overcome is it possible for germination to proceed under suitable conditions (refer to Section 1.4.1).

The testa and pericarp play an important role in this process by inhibiting access to oxygen by the embryo during dormancy.

The processes of post-harvest maturation are associated externally with a reduction in the moisture content of barley and the liberation of CO_2. In the interior of the kernel, structural elements are degraded by enzymes and converted to soluble compounds which can be utilized by the seedling. This degradation within the kernel creates fine cavities that affect the capacity of the kernel to absorb water.

The duration of dormancy may be several weeks or as long as a few months. It depends on the meteorological conditions in the field during maturation and harvesting, although the individual variety may also play a role. Dormancy can be divided into two phenomena that are likely to be stages of the same process: primary dormancy and water sensitivity.

During *primary dormancy*, it is virtually impossible for the embryo to begin to germinate, even under optimal conditions (oxygen supply, temperature, and humidity). Dormancy can be overcome by steeping the barley in a solution of 0.05% hydrogen sulfide or various other reducing agents. In addition, heating the barley or applying growth factors, such as gibberellic acid and kinetin, may be employed to overcome primary dormancy.

In Germany, for example, only physical methods for breaking dormancy are allowed, such as abrading the husks and by applying heat (refer to Section 1.5.3.9).

Water sensitivity in barley refers to the strong, negative reaction the seedlings can exhibit to excessive moisture uptake. Barley with a high water sensitivity does not germinate in a timely manner and then ceases to do so entirely as a result of a pronounced inhibition of embryonic growth through contact with water. Water sensitivity can be reduced by steeping the barley in a hydrogen peroxide solution, by extended dry rests during the steeping process, or by abrading the barley husks. Heating is only effective against water sensitivity if the barley is dried concurrently as well.

If barley is stored properly, the germinative energy and the absolute germinative capacity become closer as time goes on, although the latter must remain at its original level of more than 96%. Water sensitivity is usually highest at the end of dormancy. It can only be overcome when the germinative energy reaches a maximum.

After storage for the time required to overcome dormancy, a step in the process that *increases the value* of the grain by rendering it ready for malting, the barley must also be stored under the appropriate conditions to *preserve* its valuable properties until it is time for it to be malted. Grain is not an inert material that can be stored under any conditions; rather, it is a living organism, a plant whose respiratory products, water vapor, and heat serve to repeatedly stimulate further respiration. The resultant carbon dioxide is a respiratory toxin.

The intensity of respiration during this stage is determined by the moisture content and the temperature of the barley. An increase in temperature of 12 °C only brings about a five-fold increase in respiration, while a 2–3% rise in moisture content causes an 80-fold increase in metabolic reactions. The moisture content must be limited to 14–15% to avoid significant losses of substances or changes in the composition of the grain. The temperature should be limited to around 15 °C. At temperatures above 18 °C, there is a risk that microorganisms, such as molds and bacteria, will grow, leading to mustiness in the grain. The respiratory activity of barley and thus the loss of substances is restricted at lower temperatures and moisture levels. As they increase, changes cause the internal quality of the grain to suffer: the enzymes begin degradation processes; soluble products of degradation accumulate; and the kernel loses its rigidity as it becomes warmer and takes on moisture. In addition, the concentration of the CO_2 released by the grain increases if ventilation is insufficient, causing an ongoing shift from respiration to anaerobic metabolism or fermentation. As a result, the properties important for germination of the grain are negatively impacted to a considerable extent.

1.2.4.1 Artificial Cooling *Artificial cooling* of barley may become necessary if the existing grain dryer capacity is not sufficient to dry the barley immediately after it is harvested. The maximum time period that grain will remain "free of microbial damage" during storage is relatively brief, e.g., only 9 days at a moisture content of 20% and a temperature of 20 °C. However, grain with the same moisture content may be safely stored for 20 days at a temperature of 10 °C. Therefore, the grain must be quickly dried or cooled to below these values; otherwise, this can pose a significant danger to the barley. Furthermore, lowering the moisture content of the barley to 14% also requires reducing the temperature over time to avoid causing consequent problems with germination. Cooling techniques generally necessitate that barley be placed in ventilated granaries (see below) or silos (refer to Section 1.2.4.4) with subsequent cooling to temperatures that correspond to the period of intended storage. Mobile cooling units

are suitable for this purpose. The mobile units are attached to the ventilation equipment, so that the granaries or silos can be cooled as often as needed. For every 10 °C drop in temperature, the moisture content is automatically reduced by 0.5%. It takes around 24 h to cool 50 t of grain stored in a silo cell. The energy consumption of the air cooler is 1170 kJ/(t·h) (280 kcal/(t·h)) based on the required throughput of 25 m^3/(t·h) of air.

Therefore, it is crucial, given the conditions present when the grain is harvested with a combine harvester, that barley be dried to a moisture content no higher than 15% as soon as possible. This is especially important in Continental Europe since it is difficult to reach the requisite low temperatures before October or November. As a rule, natural cold storage is possible between November and March. In the spring, it is advisable not to move the cold barley in order to avoid warming it. At the very least, the barley must be pre-cleaned prior to storage, as extraneous seeds generally possess a higher moisture content than barley, which makes the drying process difficult. Barley dust promotes the growth of microorganisms.

1.2.4.2 Storage on Granary Floors *Storage on granary floors*: although once common, the storage of barley on floors in granaries is only rarely encountered nowadays. This storage method is the most natural, but it also demands a very large area (1.0–3.5 m^2/t). It does offer the option of selecting the depth of the grain, and when the grain is turned, the flexibility of the storage method allows adjustments to be made to the moisture content and weather conditions. If the grain cannot be turned pneumatically due to a lack of equipment, then moving the barley during storage can be quite labor-intensive. The higher the moisture in the barley, the thinner the bed of grain must be. The temperature of the grain must be monitored. Turning the grain, as with any other type of storage, serves to cool, ventilate, and dry the barley. The drying and cooling medium is the incoming air from outdoors, which can be introduced by opening windows or louvers. The outside air must be cool and dry and of course cooler than the temperature of the barley. The cool air will then be warmed as it flows through the barley, allowing it to take up moisture, thus drying the grain. Conversely, if the outside air is warmer than the barley, the air will cool down as it passes through the cooler grain, potentially dropping the temperature below the dewpoint, causing moisture to condense on the surface of the grain. Therefore, it is best to measure the moisture content and the temperature of the air utilized to dry the grain.

The vertical arrangement of several floors, one above the other, allows them to function as part of a *multi-level unit, through which the barley gradually drops*, falling through openings in the floor. From there, the kernels land on distribution plates that create thin streams of barley that then drop to lower levels.

The *ventilated storage scheme developed by Rank* enables grain to be stored in a deep layer (approximately 3 m). It consists of an open system of primary and secondary pipes outfitted with baffles and screened grills, which are either strongly ventilated with forced air from a fan for a brief period or are continuously ventilated in a gentle manner by means of rotors.

While wooden bins have been replaced by concrete bins due to their inherent fire hazards and low load-bearing capacity, concrete floors, such as those used in floor malting, may also be used to store barley, if they are outfitted to allow for proper ventilation of the grain.

A single option exists for reducing the area required for storage: barley can be stored in a deep layer in closed, tower-like buildings which are 16–40 m tall. This deep layer precludes any possible drying or ventilation, making it only suitable for storing grain with a high level of stability, preferably with a moisture content no higher than 12%. Even extremely tall silos do not have a negative impact on the grain during storage, since the pressure is shifted to the walls of the silo above 10 m.

Silos were originally constructed of wood, which offers the advantage of poor thermal conductivity and a relatively high level of permeability for dissipating metabolic products. However, as with other storage structures constructed of wood, granaries also present the same disadvantages: they pose a fire hazard, are unhygienic, and possess a low load-bearing capacity.

1.2.4.3 Reinforced Concrete Silos *Reinforced concrete silos* have been the most widely adopted construction design. They are fire-resistant, cost little to maintain, have a low thermal conductivity, and offer efficient utilization of space for large capacities. One disadvantage is the heavy weight of the building itself, which requires a strong foundation. With newly constructed silos, adequate time must be allowed for the concrete to completely set and dry in order to avoid an undesirable impact on the grain being stored inside. The cross section of the cells in the silo may be square, rectangular, honeycombed, or even irregular in shape. The

floors incline conically toward the outlet (at a 39° angle) to ensure complete discharge of the grain. Combined with horizontal and vertical transport systems, this design provides a convenient option for moving the grain without additional effort from personnel. The capacity of one silo should be able to hold the quantity of a single lot of uniform barley.

The total capacity of the silos on-premises at a malting facility should be dimensioned, so that the grain can be accepted and stored separately in different lots (according to variety and provenance) after it has been harvested. This amounts to approximately 80–100% of the processing capacity (based on the quantity of finished malt).

Since it is expensive to make concrete silos, *concrete silo modules* are manufactured as a more economical alternative for smaller installations. These are designed with a conical base that serves the additional purpose of receiving incoming barley and routing it directly to the conveyors. The manufacture of *silos without a basement* is much less expensive, even for larger units. The outer and transverse walls are set on a strip foundation, and the cell floor, inclined at an angle of 39°, is sunk into a bed of gravel. The horizontal conveyor can be accessed via a narrow gangway. The cost of construction is 20–30% less than with conventional silos. The option to utilize prefabricated, reinforced concrete components is an additional advantage.

1.2.4.4 Sheet Metal Silos *Silos made of sheet metal* are preferable to concrete silos in some respects: their construction consisting of screw-fastened steel rings or corrugated sheets is lighter in weight, less expensive, quicker to assemble, and ready for immediate use. The considerable thermal conductivity of the material promotes the formation of condensation, which limits the use of metal silos to the storage of pre-dried barley. However, the grain must also be turned in these silos as well. In general, grain stored in any type of silo (including reinforced concrete units) must be redistributed to avoid localized warming of the barley and the generation of a musty odor. Redistribution of the barley serves the additional purpose of aerating it, particularly if the grain passes through an aspiration system during transport.

Ventilation in a silo is challenging due to the high vertical column of grain. In smaller silos, the air can be pushed up through the barley from the bottom. At a height of 25 m, an air volume of 80 m^3(t·h) requires a pressure equal to a water column of approximately 500 mmAq, which is approximately 0.049 bar. Larger silo units are ventilated horizontally, with air supplied through air ducts positioned in the silo walls at defined intervals. However, aeration of the grain may only be implemented when the temperature of the outside air is lower than that of the grain in the silo. The dust must be removed from the exhaust air that escapes when filling the silos or during ventilation of the grain in storage. At malting facilities with larger silos, the air passes through dust removal equipment on premises (usually filters). In smaller malting operations, exhaust air exiting the silo is routed through the dust removal units found in the systems for cleaning and transporting grain.

A large silo requires precise temperature control at different heights, preferably with probes capable of sending the values to a dedicated silo control and monitoring station. If the temperature in a certain layer of grain rises by 2 °C within 48 h, the grain must be redistributed. Samples should also be collected to determine the moisture content, germinative capacity, and germinative energy.

The control switches and signal lights for the conveyor systems and cleaning devices are also part of the *silo control panel*. A series of sequential switches and locking mechanisms represent one line of prevention against incorrect settings and ensure that different sets of bulk materials are not mixed, e.g., barley and malt.

1.2.5 Artificial Drying of Barley

The technical advancements offered by modern combine harvesters, the short-term delivery of large quantities of barley to the malting plant, and the sheer impossibility of cooling and drying the barley within the required period, even with ventilated silos, have resulted in the swift adoption of artificial drying. When properly treated, the grain is not only stable throughout storage, but rapid drying also brings about an immediate improvement in germinative energy. Therefore, grain should be dried as quickly as possible.

Reducing the moisture content of barley by artificial means is only possible under certain conditions: for example, the barley must be fully mature on the stalk, and care must be taken during pre-cleaning to remove extraneous seeds and contaminants because they are more hygroscopic than barley and are therefore harder to keep dry. The husks on the barley impede the removal of water vapor from the kernels, thus hindering the drying process.

Since risk-free storage is guaranteed only at a moisture content equal to or below 12%, efforts

should be made to dry the barley until a suitable moisture content is reached. Drying to a value of less than 10%, however, is not only uneconomical, but it also poses the risk of negatively impacting germination later. The artificial drying of grain can be accomplished through heating or cooling. Drying with heat is preferable from an economic standpoint. As heat is applied, the vapor pressure increases inside the kernel, so that it exceeds that of the air used for drying. The greater this difference is, the more rapid and extensive the drying process is. Nevertheless, the degree to which heat is applied is strictly limited, as the barley is very sensitive to temperatures above 50 °C. The higher the moisture content is in the barley at the beginning of the drying process, the lower the air temperature used to dry the barley must be. Even though barley with a moisture content of 16% may be heated to 49 °C, in order to protect the seedlings from damage, a temperature of only 34 °C is permissible for barley with a moisture content of 22%. It is recommended that extremely moist grain be dried in two stages, e.g., from a moisture content of 20% to 16%, followed by another reduction from 16% to 12%.

Barley lots, which exhibit pre-germination, cannot tolerate extensive drying with subsequent warm storage to overcome dormancy. This applies to both visible and hidden pre-germination. In this case, it is better to store the barley at normal, or even at cooler temperatures, and continuously monitor the progress made in overcoming dormancy. Once dormancy has been broken, the barley should be malted immediately after it demonstrates a reasonable amount of germinative energy. If this cannot be achieved, the barley is unsuitable for malting and brewing.

In older dryers, the direction of the air flow switches intermittently between the side of the grain layer that is drier and the side that is less dry near the outlet for the exhaust air. This can result in damage to the germinative capacity when higher temperatures are used to dry grain with an elevated moisture content.

1.2.5.1 Modern Dryers *Modern dryers* eliminate the need for preheating (pre-sweating), previously considered indispensable, in which the grain was heated to 35–40 °C without any input of air. Preheating and drying were carried out in separate sections of the tower, which was intended to draw the moisture from the interior of the kernel through the capillaries to the outside surface. The moisture could then be easily evaporated during the subsequent light drying of the kernels. In modern dryers, the air no longer flows through open-bottomed ducts (in the shape of an inverted "V") in an offset vertical pattern but rather in a diagonal arrangement. As a result, the flow of grain is constantly diverted into different streams. By omitting a row of air ducts in the upper third of this section, drying is uniform, allowing the same moisture level to be achieved in each of the product streams. This, in turn, reduces the thermal stress on the barley, preventing losses in germinative capacity.

New drying plants consist of 13 modules for drying and an additional 3 modules for cooling to 10 °C above ambient temperature. The air for drying is heated with a hot air generator using gas or oil. The air is heated to a temperature of 60–65 °C. After heating, a suction fan moves the air into the dryer from above. This high temperature is feasible because the air will subsequently be cooled through the evaporation of moisture on the surface of the grain. Nevertheless, depending on the moisture content of the barley, the temperatures noted previously must not be exceeded. Modules 10–13 receive air directly from the heating unit, though the exhaust air from the modules 11–13 is recirculated in the system. Compressed air is used for cooling in modules 14–16. The heat emitted there can be recovered by returning it to the air heater. The malting barley spends 110 min in the dryer.

The throughput of dry air is 3600 $m^3/(t \cdot h)$. The thermal energy required is approximately 194,000 kJ/t of barley (51,600 kcal). An energy savings of 10% is possible if the heat liberated from the cooling process is recovered and utilized. The plant draws 2 kWh/t of electricity during operation.

A suitable location for the dryer is between two silos. The capacity should reflect the quantity to be dried over a 10 h period. The amount of water extracted from the grain is determined by scales positioned above and below the dryer.

1.2.5.2 Malt Kilns A *malt kiln* is also suitable for drying barley. From a technical perspective, a single-floor, high-performance kiln with a tipping floor is preferable; 400 kg/m^2 of barley can be dried on this type of kiln floor within 6 h by increasing the initial temperature from 35 to 45 °C, which causes the moisture content to drop from 20% to 15%. Any differences in moisture present between the upper (16%) and lower (12%) layers will eventually even out over the course of treatment. Drying one metric ton of barley requires 255,000 kJ (60,000 kcal) and 7–8 kWh. The kiln can be loaded up to three times within a 24 h period. The temperature difference between the air at the inlet and at the exhaust serves as a criterion for how well the drying process is progressing. The capacity

of a kiln floor with an area of 50 m^2 is equivalent to 20 t per batch. This corresponds to 60 t per day and is therefore comparable to the capacity of a continuous dryer which can process 2.5 t/h.

The difference in moisture between the upper and lower layers can be reduced as follows: first, the air is recirculated for 1 h at 40–45 °C, followed by drying at 50 °C with fresh air and venting of the exhaust air. This temperature is reduced to 40–42 °C after 30–60 min of drying.

Further options for drying include box pallets or silos equipped to ventilate and dry the grain. In these cases, a heating unit with a fan for heating and drying grain is connected to a barley storage unit. The outside air is used for cooling and ventilation.

After drying, it has been customary to cool the barley with fresh air and then transfer it to the storage area. In general, the following procedure for overcoming dormancy has proved to be efficacious. Barley with a moisture content of 12% is stored in a silo at a temperature close to 35 °C until the dormancy is lifted. This usually takes between 3 and 14 days. Progress is monitored by conducting a "forced" 4 ml/8 ml test (72 h) every 3 days, at the very least. Once dormancy has been overcome, the grain is cooled by redistributing it (by passing it through an aspirator). This procedure also lowers the water sensitivity. Another method is to cool the barley coming from the dryer with dehumidified air to 6–8 °C and then store it in silos.

1.2.5.3 Drying with Cold Air *Drying with cold air* has not become widely established for economic reasons. It would be more convenient than drying with heat because the grain is cooled to a greater extent, given the same amount of moisture extraction. Grain stores more favorably at cooler temperatures, and the metabolic processes are greatly reduced. The lower temperatures discourage pests from taking up residence. This knowledge is applied in the cold storage of barley (refer to Section 1.2.4.1). With freshly harvested or overly sensitive barley, there is a danger that dormancy will not be overcome in the barley and, instead, its dormancy will simply be prolonged. This phenomenon is referred to as secondary dormancy.

1.2.6 Plant Diseases and Animal Pests Affecting Barley

Depending on meteorological conditions during barley growth, maturation, and harvest, the grain contains varying amounts of microorganisms, which can greatly affect it during storage. Plant pathogens may attack and cause damage while the crop is still in the field, or contamination may occur during storage.

The former encompasses various fungi (including those that are responsible for smuts and rusts) and ergot, in addition to molds such as *Rhizopus*, *Mucor*, *Stemphylium*, and *Fusarium* species. Since 1987, *Fusarium graminearum*, *F. culmorum*, and *F. avenaceum* have been linked to gushing, a phenomenon that causes spontaneous overfoaming of beer (refer to Section 7.6.8). Given sufficient amounts of rainfall, these *Fusarium* species may infest the crop at the peak of flowering, entering the anthers and penetrating the endosperm to utilize the nutrients present there. Gushing is caused by the metabolic products of fungal growth, which include peptides, polar lipids, and carbohydrates. Prior research has shown that hydrophobins, i.e., extracellular fungal proteins exhibiting high surface activity, also play a major role, along with a lipid transfer protein derived from barley (refer to Section 1.4.1.2). A number of other molds found on grain originate from the field but develop first during storage. These molds are capable of forming toxins that not only destroy the germinative capacity of the grain but also significantly reduce the value of the grain as feed. These include species belonging to *Aspergillus* and *Penicillium* in addition to those mentioned previously.

Insect pests first appear in stored grain, e.g., grain weevils and grain moths. The grain weevil lays its eggs in the barley kernels, and the resulting larvae eat the kernels from the inside, leaving hollow kernels. The infestation is only evident when the weevils come out of the kernels, for instance, when grain is moved, exposed to light, or warmed. Grain weevils are usually brought into the facility through transport on ships or by other means, e.g., through infested grain that has been bagged and brought into malting facilities. Weevil-infested grain must be rejected without exception.

Weevils can be driven out of the grain or even eliminated by frequently turning or cleaning the grain. Nevertheless, chemical agents provide a far more effective means of control. Insecticides may be painted on, be administered in gaseous form, or accomplish their intended function through other forms of contact. Multiple prerequisites exist for the application of pesticides. The agents must be completely removed after treatment, and they may not change the physiological process of germination and the enzymatic reactions that occur during beer production. Furthermore, there should be no sensory alteration perceptible in the finished beer.

The chemicals also cannot be hazardous to human health.

Large silos must be equipped with their own gas-generating equipment to protect the stored grain quantities safely against infestation, or they should be otherwise equipped to destroy any pests that might appear.

1.2.7 Changes in the Weight of Barley During Storage

During the storage of barley, changes in weight occur primarily as a result of the evaporation of moisture and due to respiration. The extent of these losses depends on the moisture content of the barley. These changes are readily evident, particularly in the three months after the harvest. Over the course of a year, approximately 1.3% is lost during the first three months, 1.0% is lost in the subsequent three months, and around 0.8% in the second half of the year. Longer storage times for malting barley generally only come into question if the crop is to be stored over the summer. In this case, reducing the moisture content of the barley to 12% is an absolute necessity.

1.3 Steeping the Barley

Barley will only begin to germinate above a certain moisture content. Barley in storage has a moisture content of at least 12% (capillary water). It should be low in order to keep signs of life in the barley to a minimum. Only with the addition of more water will germination be initiated. Signs of life in the kernel exhibit a significant escalation at a moisture content of approximately 30%; at c. 38%, the barley germinates at its most rapid and uniform rate. However, a moisture content of 43–48%, or in some cases even greater, is necessary to facilitate the development of the enzymes and to achieve the desired level of modification in the endosperm. The majority of the moisture required to launch germination is supplied during the steeping process. Nevertheless, the moisture content of the barley first reaches its maximum during germination. The steep liquor should exhibit a quality level equivalent to that of normal drinking water. It should also be free of any impurities of a physical, chemical, or biological nature. Although the pericarp and testa of a barley kernel are semipermeable, ions in the steep liquor can diffuse across these structures into the endosperm (refer to Section 2.1.3.1). Diffusion occurs through certain gaps in the testa located in close proximity to the embryo. As a result, germination may be inhibited, for example, in the presence of ions such as NO_2^- (nitrite). The concentration of the ions present in the steep liquor is usually so low that no direct consequences of their presence are observed.

1.3.1 Moisture Uptake in the Barley Kernel

Water imbibition occurs predominantly through the vascular tissue at the base of the kernel. Moisture uptake is slower on the sides and at the distal end of the kernel. For this reason, the individual areas of the kernel initially exhibit different levels of moisture, though the moisture level gradually evens out.

The rate of moisture uptake is by far most rapid in the first 4–8 h but declines quickly as the moisture content approaches the saturation level. This is determined by the capacity the barley has for water imbibition.

The activity of the amylases, ribonuclease, and the phosphatases rises in parallel with the moisture content during the first 6 h of steeping. As a result of the lack of oxygen, they decline in the embryo and the endosperm, only to rise again during the ensuing air rest.

At a moisture content of 41% across the entire kernel, the embryo itself has a moisture content of 65–70%. During the air rest that follows, the embryo begins building tissue and competes with the endosperm for moisture due to its increased demand for water. During this time, the embryo withdraws a portion of the water already absorbed by the endosperm. Water transport comes to a standstill at a moisture content of 36% in the endosperm. The water adhering to the surface of the kernel after steeping is primarily absorbed by the embryo. However, germination intensifies if the film of moisture is eliminated. This is also the case if the water adhering to the surface is swiftly taken up, which is the intention behind limiting the time spent in steeping and air rests. Limiting the length of these rests plays an important role in rapid and uniform germination. The embryo in a kernel of barley cultivated and harvested under hot and dry conditions possesses a high level of vitality. The embryo takes up copious amounts of moisture and also draws off some of the moisture from the endosperm during the subsequent air rest. As a result, the moisture uptake by the endosperm occurs haltingly over the course of the entire steeping process. Therefore, the air rests have to be curtailed, which the barley tolerates quite well due to its low water sensitivity. In contrast, barley cultivated under wet conditions exhibits a more

rapid moisture uptake and a more homogeneous distribution of the water throughout the kernel. Thus, longer air rests are required. In this case, the rests do not impact the uniform distribution of moisture throughout the endosperm as strongly and are instrumental in overcoming the higher degree of water sensitivity exhibited by this barley. Therefore, the steeping process can be devised, so that it addresses the structure of the endosperm while at the same time taking the physiological properties of the embryo into consideration.

Moisture uptake is further dependent on the size of the barley kernels (sorting). Plump kernels take longer than thin ones to reach the same moisture content.

However, the differences that become apparent with regard to moisture uptake are also dependent on the steeping process. For example, a pure wet steeping rest, or one in which steeping predominates, serves to accentuate differences in the water imbibition of large and small kernels. Conversely, extensive air rests can compensate for these varying rates of moisture uptake in barley to such an extent that they allow barley of grades I and II to be steeped together. The moisture content of the barley at the beginning of the steeping process is of no consequence; however, the structure of the kernel is. The structure is influenced by whether the growing season was dry or wet. The water imbibition of barley occurs more slowly when the grain matures under dry conditions or has not yet reached the point it can be malted, that is when its water sensitivity is still high. The moisture uptake of protein-rich barley only evinces a slow uptake if the structure of the kernel is negatively influenced by unfavorable conditions during cultivation and harvesting (see above). Otherwise, barley of the same provenance from a single crop year exhibits no differences. Additionally, water imbibition is dependent on the variety of barley.

Concerning the *temperature of the steep liquor*: the warmer the steep liquor is, the more rapid the moisture uptake in the kernel. On average, conventional steeping temperatures are 10–12 °C. The ions in the steep liquor, that is, the hardness of the water, do not play a role in the imbibition of the kernels. In order to achieve a moisture content of 43% for the same sample of barley, the following steeping times are necessary for steep liquor at different temperatures: 78 h at 9 °C, 54 h at 13 °C, 46 h at 17 °C, and 28 h at 21 °C. Steep liquor at 12–13 °C is the most favorable temperature from a physiological standpoint when steeping rests, rather than air rests, are employed for the majority of the process.

Concerning the *overall steeping regime*: Moisture uptake is not as rapid with pure steeping rests compared to a regime with intervening air rests. Long, dry intervals between the steeping rests have been demonstrated to be particularly advantageous. Within the context of a total duration of 46 h, a 9 h steeping rest is ample for reaching a moisture content of approximately 43% as discussed above.

1.3.2 Supplying Oxygen to the Steeping Grain

Besides water imbibition, there are other processes at work as well. As the moisture content increases, the kernels begin to require a substantial amount of oxygen to carry out respiration.

Oxygen is necessary for *any activity associated with signs of life* in the kernels, which must be available in sufficient quantities throughout the steeping process. For every molecule of oxygen taken up by the kernel during respiration, the kernel likewise eliminates one molecule of carbon dioxide. The ratio of CO_2:O_2, or the respiratory quotient, is therefore equal to 1.

Metabolism in the kernel is anaerobic if the respiratory quotient is greater than 1. The resultant metabolites, alcohol and carbon dioxide, are poisonous to the developing embryo. Poisoning occurs more rapidly when the kernels are submerged in steep liquor than in the air. Over the course of the steeping process, the kernels must tolerate alcoholic fermentation to a small extent – even under optimal oxygen conditions – until chitting occurs. At that point in the steeping process, the embryo is able to break through the husks, which very tightly enclose the kernel due to prior absorption of the steep liquor. Shortly after chitting, the accumulated alcohol begins to dissipate as a result of intracellular oxidation. Even an alcohol content as low as 0.1% can cause uneven growth. If steeping is carried out properly, then the amount of alcohol is insignificant, but it can reach several percent in the absence of oxygen. Intramolecular respiration commences in association with the accumulation of carbon dioxide, and an estery, pungent aroma emanates from the steeping barley. In extreme cases, a putrid odor becomes apparent, and the kernel loses its firmness. Barley with a diminished vitality also absorbs an excessive amount of steep liquor. This is referred to as oversteeping or a "dead steep." The germinative capacity of the barley is partially lost as a result.

It is of particular importance to understand that, above all during the steeping rest, it is not possible to distribute oxygen uniformly throughout the

grain in the steeping vessel. When air is blown in, the oxygen concentration is highest at the bottom and decreases toward the top. If liquor is fed continuously into the steeping vessel from the bottom, the oxygen in the liquor is already consumed by the time it is midway up the vessel. Aeration and the dispersal of oxygen during the steeping rest is more effective in a flat-bottomed vessel than in a cylindroconical tank. However, supplying oxygen to the grain during steeping is best accomplished with a cylindroconical tank equipped with an injector for compressed air. The air is blown in through a centrally situated, vertical pipe, which vigorously circulates the entire volume of the liquor/grain mixture.

The oxygen requirement is particularly high for barley still exhibiting water sensitivity. This kind of barley has recently overcome its dormancy or was not stored properly (refer to Section 1.2.4). The water sensitivity can be alleviated with an ample supply of oxygen and long air rests, which will allow germination to take place in a uniform manner.

1.3.3 Cleaning the Barley

Steeping also facilitates the cleaning of the barley. The ions in the steep liquor react with the substances in the husks, leaching substances from the husks and cleaning them. The more hydrogen carbonate there is in the liquor, the stronger this effect is. The effect can even be intensified by more vigorous movement of the grain when transferring it to the steep and during the first steeping phase. The submerged grain can be aerated using perforated rings mounted in the vessel or by means of a compressed air injector and a centrally positioned, vertical air-lift tube. The once common addition of alkali or hydrogen peroxide is no longer permissible under the current laws governing foods.

Cleaning the grain prior to steeping will optimize the function of the process and reduce the amount of wastewater generated. This can be achieved by intensive mechanical cleaning of the grain upon delivery in addition to a primary cleaning step before steeping begins. The movement and abrasion due to the action of conveyors and in dust removal systems (refer to Section 1.2.3) enhance this effect.

Cleaning with water can be improved by means of a washing drum, as is employed, for example, in loading flat-bottomed steeping tanks. A grain cleaning auger used to wash the grain with water also exerts a strong mechanical cleaning effect.

Washing the barley should remove not only the normal impurities but also the microflora from the field and from storage. Furthermore, as mentioned previously, soluble compounds are also leached out of the husks. These substances comprise, among others, phenolcarboxylic acids, polyphenols, and lipids and are capable of inhibiting germination. They are also among the bitter compounds derived from the husks.

Warmer steep liquor, for example at 25 °C, not only achieves slightly better results with regard to cleaning the grain but also leaches the substances in the husks out more effectively during the first steep. Especially during the colder months, warmer liquor raises the temperature of the grain, which then results in a more rapid uptake of the steep liquor. It is imperative that zones of different temperatures are not allowed to form (on the inside/outside and at the top/bottom), which can give rise to uneven water imbibition. Moreover, the lower temperature steeping rest that follows may shock the grain at this early stage. For this reason, the 15 min "hot water steep" at 40–50 °C suggested previously cannot be put into practice. Grain cleaning augers or washing drums afford not only more effective cleaning with approximately 30 °C water but also more rapid imbibition early on during the steeping process.

The microbial content of the steep liquor is theoretically irrelevant when compared with the large number of microorganisms introduced by the barley. Nevertheless, it must comply with the stipulations laid out in the local regulations governing the quality of the drinking water; e.g., it must not contain any pathogens. If the steep liquor is reused, then it must also be of a quality that fulfills the legal requirements for water purity. In addition, it is essential that the liquor employed for steeping barley is neutral in both odor and taste (refer to Section 1.3.4).

1.3.4 Water Consumption

In theory, achieving a moisture content of 47–48% in the barley to be germinated only requires 0.7 m^3/t. However, water consumption during the steeping process is substantially higher in practice, depending on the method and the equipment used. The volume of liquor necessary for steeping is 1.8 m^3/t of barley. Pumping out and replacing the steep liquor requires 1.2 m^3, and a single transfer from one steep to another with a pump necessitates 1.5–1.8 m^3. Casting the steep out "wet," as it is termed, consumes 1.8–2.4 m^3. An alternating wet/dry steep, which was once common

practice, comprised seven liquor additions, and the entire volume was recirculated twice. Along with wet casting, the total water consumption was 11 m^3/t. By contrast, a modern steeping process consists of three liquor additions and consumes no more than approximately 5 m^3/t. By adjusting the steep liquor overflow to the volume of barley in the tank and omitting recirculation with a pump – if intensive recirculation with compressed air is feasible – the water usage can be reduced by another 0.8–1.5 m^3/t. A reduction in the number of steeping rests demands a correspondingly higher amount of spraying to increase the moisture content during germination. The use of grain cleaning augers enables an even greater reduction in water consumption. Despite the liquor being heated (up to 30 °C), the moisture content of the grain only reaches about 25%. The water consumption in this case, depending on the intensity of the cleaning process, amounts to 1.0–1.2 m^3/t.

Similar rates of water consumption also occur with a washing drum. The consumption rates provided above are based on steeping vessels with conical bottoms. In a normal flat-bottomed steeping vessel, the grain/liquor mixture reaches a height of 1.70 m over an empty space below the deck of about 70 cm. Together, these amount to $1.15 + 0.72 = 1.87$ m^3/t. With two steeping rests, the total volume would be $1.87 + 1.87 = 3.84$ m^3. By casting out the steep wet, the liquor below the floor becomes part of the total volume. Therefore, a volume of 4.74 m^3/t of barley is necessary if the supplemental steep liquor is considered. The lower water consumption compared to a conical steeping vessel is a result of the equipment used to cast out the grain/liquor mixture. By virtue of how it is designed, the water usage in casting out the steep from a flat-bottomed steeping vessel is inevitably lower than one with a conical bottom.

The dead space is eliminated in a so-called "economical steeping tank" (*Ökoweiche* in German), as there is no space under the deck. When casting out the steep dry, a process with two steeping rests only requires a water usage of 2.3 m^3/t of barley.

If the steep liquor is exclusively applied by means of spraying in the germination system, the water usage amounts to 0.9 m^3/t, a figure slightly above the theoretical value. However, this method demands intense mechanical cleaning of the barley prior to the steeping process.

Steep liquor must be treated prior to its reuse. It contains microorganisms and substances that inhibit germination as well as other impurities resulting from the forces of friction acting on the grain. Moreover, the frequent manifestation of gushing in beer also makes the reuse of steep liquor unacceptable. The odor of the wastewater is often disagreeable, especially that recovered after casting out, i.e., water recycled from the germination vessel. Contamination may spread further throughout the facility when the wastewater is stored, since vessels are needed for the storage of wastewater between the time it is collected and reused.

One of the current techniques for treating wastewater employs a single-stage membrane bioreactor (MBR), a variant of the activated sludge process, to treat the wastewater recovered from the barley cleaning process. As part of this process, the wastewater is intensely aerated and exposed to an active population of bacteria, which degrades the organic substances in the water. A precipitating agent, e.g., iron chloride, is used to further treat the water before it is passed through a polypropylene capillary membrane (ultrafiltration). The membrane has a pore size of 0.01 µm, which is small enough to retain bacteria and even viruses. The next step in the process is reverse osmosis treatment and charcoal filtration. The water quality should then meet or fall below the limits for both conductivity and chemical oxygen demand (COD), e.g., as outlined in the German regulations governing drinking water *Trinkwasserverordnung* (TVO). Only 60–70% of the water can be recovered due to losses incurred during the treatment process. In order to restore the mineral content, fresh drinking water must be added to the treated water at a rate of 30–40%. The considerable technical complexity and the accompanying monetary outlay generally discourage this practice among maltsters. However, the rising costs for drinking water and third-party wastewater treatment may lead to a rise in on-site recycling (treatment and reuse). In fact, on-site treatment is already being practiced where more intense washing of barley is carried out.

1.3.5 Steeping Equipment

1.3.5.1 Types of Steeping Vessels *Steeping vessels* are made of steel sheets, stainless steel, or reinforced concrete. Stainless steel eliminates the need for food-safe coatings on the vessels and also simplifies cleaning and maintenance. For this reason, the interior of concrete steeping tanks is now usually clad with stainless steel sheeting. Uniform handling of the steeping grain is facilitated by a steeping vessel with a cross section that is either round or square. In order to expedite the emptying of the steep, the bottom is usually conical in shape. Large, rectangular vessels may be divided at the bottom

into individual square sections, each with its own conical outlet.

1.3.5.2 Steeping Vessel Capacity The *capacity of a steeping vessel* is calculated according to the quantity of barley and the increase in volume of the barley during steeping as well as the additional space required for agitation. Taking this into consideration, the volumetric capacity for steeping 1 metric ton of barley is 2.2–2.4 m^3. A steeping system should be dimensioned with a total capacity that encompasses the maximum possible duration of the process. This comprises the time needed for loading, steeping, casting out, and cleaning. An occupation time of 45–48 h is considered necessary for modern steeping processes. This entails the installation of two steeping units. It is often the case that the steeping process is reduced to 24–28 h, with the initial phase of germination occurring in the germination vessel, which would then only necessitate one or possibly two steeping units. If the duration of steeping is limited even further, under certain circumstances, the air rests may be curtailed so stringently that their physiological effects on the kernels can no longer be attained. The number of steeping vessels per system depends on the capacity of the germination system. In order to be able to evenly steep the grain, the individual steeping vessels should have a capacity no larger than 50 t. Similarly, if the steeping vessels are too deep, as their depth increases, aeration becomes difficult, causing subsequent germination to proceed unevenly. Larger steeping vessels are thus rectangular with numerous conical outlets or hoppers integrated into the base.

1.3.5.3 Positioning Steeping Vessels The *steeping vessels are best positioned* between the barley hoppers and the germination system. Given the option of casting out wet, however, a position in close proximity to the germination system has become less important.

1.3.5.4 Steeping Chambers The *steeping chamber* should not be affected by outside temperatures but rather should be adjustable to a temperature range of 12–15 °C by heating in winter and cooling in summer. Furthermore, the moisture in the air should be around 85–90% since, for example, the moist air is pulled through the steeping barley by the CO_2 exhaust fans.

In order to avoid having to moisten the air for the entire room, it may be helpful to install covers over individual vessels and to place a device for humidifying the air and regulating the temperature under each one.

The equipment associated with steeping vessels has become much more complex than it was in the past. Pumps for recirculating the steeping barley and devices for aeration with compressed air, for carbon dioxide removal, and perhaps for spraying the barley add to the already customary steep liquor supply and drain lines, the outlet for casting out the steep and an overflow to remove the floating barley.

1.3.5.5 Steep Liquor Supply and Drain Lines The *steep liquor supply and drain lines* should enable rapid drainage and refilling of the steeping vessel in order to precisely adhere to the steeping schedule. The time required to fill each vessel should never exceed 1 h.

Spraying the barley using nozzles serves less to supply the vessel with liquor than to condition the air entering the grain bed through the top. Spraying may also be employed to counter a rise in temperature under certain circumstances. The nozzles must be arranged so that they cover the entire surface of the steeping barley.

1.3.5.6 Recirculation Using Steeping Pumps *Recirculation* is implemented by means of steeping pumps, which are designed, similar to the valves used for this purpose, to gently move the steeping barley without damaging it, even barley at the forking stage of germination. The wastewater can largely be removed through pumping from one vessel to another through a system of perforated separators. Pumping the steeping barley undoubtedly results in a thorough cleaning of the grain, but it does not satisfactorily redistribute it, since the portion in the cone usually ends up there again.

1.3.5.7 Compressed Air *Compressed air is delivered* by means of simple, portable rousing devices in small steeping vessels, and through vertical air-lift pipes in larger ones. In both cases, the steeping barley is agitated by means of compressed air from below and tossed upward together with the steep liquor. Sometimes, the distribution of barley takes place by means of a swivel arm. Finely perforated diffuser rings, mounted inside the cone of the steeping vessel, are also utilized to facilitate the fine dispersal of compressed air. An aeration ring with the appropriate mass air flow (approximately 15 $m^3/(t \cdot h)$) is considered sufficient to circulate the barley within the vessel. The first steeping vessel is equipped with several aeration rings, which may be turned on and off individually as needed. Compressed air is usually warm since it is under 2–5 bar of overpressure; therefore, it is possible that the temperature in the steep may rise during the 10–15 min of aeration. If circulation

of the steep liquor/barley mixture is sufficiently intense simply through aeration, then pumping it around in a loop can be dispensed with if each steeping vessel is properly outfitted for steeping in and casting out. As a result, a considerable amount of water can be saved since the additional water required for transfer is not needed.

1.3.5.8 Carbon Dioxide Removal Carbon dioxide is removed from the bottom of the steeping vessel through the suction of exhaust fans. This draws the gas through the grain bed to the bottom of the cone where it is removed. If only carbon dioxide is to be removed, then an exhaust fan with an air flow rate of approximately 15 $m^3/(t \cdot h)$ operating for 10–15 min every hour is sufficient. However, if the barley not only has to be freed of CO_2 but must also be aerated and cooled during extensive air rests (12–20 h), an air flow rate of 50 $m^3/(t \cdot h)$ is required on the first day of steeping. A volume of 100–120 $m^3/(t \cdot h)$ must be supplied on the following days. If existing steeping vessels are retrofitted with stronger fans, it is recommended that mesh screens or an additional mesh cage be installed on the walls of the lower third of the cone to permit the desired flow of air.

1.3.5.9 Flat-bottomed Steeping Vessels *Flat-bottomed steeping vessels* are usually round with a horizontal, perforated deck mounted above the bottom. The grain bed fills the vessel to a height of 1.7–2.0 m (1200–1500 kg/m^2) above the deck. The plenum or the space beneath the deck is approximately 70 cm deep, which automatically results in a higher consumption of steep liquor (refer to Section 1.3.4). Loading and unloading are carried out by a rotary device, normally with multiple arms, known as a giracleur. The device can be raised or lowered; adjustable paddles allow uniform spreading or complete removal of the steeping grain. While the grain is submerged under the steep liquor, aeration is carried out with compressed air blown through fixed nozzles or through nozzles attached to perforated pipes which can be rotated. In particular, the latter can be used to clean the false floor from below as well as the plenum chamber under the deck. Suction is used to draw carbon dioxide off the grain from the bottom of the vessel where it is removed. An exhaust fan with a capacity to move air at a rate of up to 200 $m^3/(t \cdot h)$ is usually equipped with a variable frequency drive to allow the airflow to be adjusted appropriately for a given stage of steeping (e.g., depending on the temperature of the steeping grain or the temperature difference between the supply air and the exhaust air). The abovementioned volumes of air must, of course, be attempered and conditioned. The steeping vessel is covered by a flat lid or a dome. If steeping commences in a cylindroconical tank, the vessel for the second day of steeping is often cuboid in design. This vessel is equipped with compartments with perforated decks, which can be raised and lowered. The steeping grain is moved according to the principle of the "transposal system" (refer to Section 1.5.3.5) with a device for spreading and removing the grain. Casting out takes place using a container for removal of the grain. The grain can be transferred to the germination box when wet or dry. Since the perforated decks cannot be lowered below 1 m above the bottom of the chamber, the steeping grain is never completely submerged in steep liquor and is moistened through intermittent dowsing or spraying using the turner, while taking care to avoid the formation of channels. If casting out wet, a very short steep can take place in the container used to remove the steeping grain.

A new type of flat-bottomed steep is more environmentally friendly because there is practically no plenum space under the perforated deck, which is situated at the bottom of the vessel. Supplying and draining the steep liquor, aerating with compressed air when the grain is submerged, and removing the carbon dioxide during the air rests are all carried out over a number of collection points distributed evenly over the entire floor. These substances enter and exit through a pipe with a conical inlet, designed to create favorable conditions for the liquor to flow in and out and for the carbon dioxide to be drawn out for removal. The compressed air enters through dedicated narrow gauge supply lines in the cones of the collection points. The specific floor load for this type of steeping vessels is 1000 kg/m^2, with a total capacity of up to 550 t. The height of the grain bed is 1.4 m. The plenum chamber under the deck is 2 m high and encloses the entire network of pipes in the system. By eliminating the plenum under the deck, it is possible to save up to 40% of the liquor or wastewater compared to earlier designs for flat-bottomed steeps. Maintaining the cleanliness of the system, especially that of the periphery, is of great importance.

These large steeping vessels must be able to be loaded and unloaded in as short a time as possible. For this reason, the conveyors must be large enough to carry out loading and unloading within 2 h. In tower malting facilities, flat-bottomed steeps are located on the uppermost floor. If they serve as an extension of an existing facility, then

a fully climate-controlled and insulated space must be created. In this case, conveying the grain becomes somewhat more difficult, especially when casting out the steeped grain. In this case, grain washing augers or washing drums are practical for loading the steeping vessel.

The steeping auger is tilted upward at an angle of 30–35°. The basin of the auger trough is designed so that the grain is covered by a layer of steep liquor (50–30 cm). In order to convey the grain at the necessary volumes during steeping, several augers must operate next to one another. For example, a steeping system designed for 90 t/h is equipped with five augers situated side by side. Two sets of augers are necessary for moving higher volumes. Due to the intensive contact of the barley with the liquor flowing in the opposite direction, the resulting abrasion cleans the grain very effectively. Even if the liquor is heated, the moisture content of the grain nonetheless rarely exceeds 25–30% in such steeping systems.

A grain washing drum can also bring about an intensive cleaning of the grain. Over the course of 30–45 min, the drum moves the barley entering at one end to the outlet at the other end by means of buckets arranged in a spiral fashion on the inside wall of the drum. The water used in the drum flows countercurrent to the grain, so that the grain at the outlet end of the drum comes into contact with fresh water. The drum is approximately one-third full of water. Depending on its size and throughput, the drum is capable of processing 20–60 t/h. The moisture content at the end of cleaning process is comparable to that of the grain washing auger described above.

1.3.6 Steeping Technology

1.3.6.1 Conventional Steeping *Conventional steeping* in its simplest form is carried out as follows: the barley slowly enters the steeping vessel over a spreader cone, the denser grain gradually sinks to the bottom, while the barley that floats, along with the other impurities, remains at the surface. The material on the surface passes through an overflow or is skimmed off as "floating barley," which is subsequently collected and dried. The amount varies between 0.1% and 1%, depending on the degree of purity of the barley. Strong aeration brings about intense movement and thus a more thorough cleaning of the grain. Impurities on the surface are washed away by filling the vessel with steep liquor to the point that it overflows. The steep liquor is changed after 12–24 h. How frequently this occurs is subject to the degree of purity of the barley, the liquor temperature, and the duration of the steeping process. The grain remains unsubmerged several times between changes of the steep liquor. This measure allows for better aeration of the grain, since barley submerged in steep liquor for the entire duration of the steep consumes the oxygen dissolved in the liquor within a very short time. Over the course of the development of modern steeping processes, air rests have been expanded to comprise as much as 50%, even sometimes 80%, of the total duration of steeping. The liquor clinging to the surface of the kernels not only increases the moisture content during the air rests but also shortens the total duration of steeping and accelerates germination.

In a conventional steeping process, the grain is submerged and aerated normally for 10 min every 1–2 h. During the air rests, it is necessary to remove the carbon dioxide for 10–15 min every 1–2 h. By the end of this period, 3–5% CO_2 by volume will have been generated; however, the quantity depends on the stage of the steeping process.

Recirculation can only take place when the grain is submerged in liquor. Generally, this occurs twice over the course of a 60–70 h steep. On occasion, a portion of the wet steeping period is replaced by spraying the grain with steep liquor instead.

1.3.6.2 Modern Steeping Processes *Modern steeping processes*: methods for supplying the grain with moisture, which have been developed through practical experience, are quickly being replaced by processes utilizing short wet steeping periods interspersed with long air rests to reach the desired degree of moisture in the grain. The longer dry periods induce very specific physiological processes to occur in the grain. The water sensitivity of the barley declines at a moisture content of 30% coupled with a 14–20 h air rest. At a moisture content of approximately 38%, uniform germination of the grain is expected within a period of 14–20 h. The duration of the air rests is largely dependent on the water sensitivity of a barley, which is not as pronounced if weather conditions are hot and dry during the time the grain ripens and is harvested. However, the water sensitivity can be high if the final phase of the growing season is cool and moist. Thus, for the barley grown under hot and dry conditions, an air rest of only about 14 h is necessary, while barley cultivated under cooler, wetter conditions may need an air rest of 20–24 h. The duration of the second air rest, which is characterized by the "chitting" of the barley, is also influenced by these conditions. The practice

of adding moisture to the grain before uniformly spreading it out is completely unsound, even if this is only accomplished through spraying. This inevitably results in uneven growth. Casting out wet results in a moisture content of 42–43%. The final moisture content is reached in the germination system through spraying the grain properly. In order to ensure uniform treatment of the grain, it is essential to recirculate the grain with compressed air during the wet steep. A nozzle to deliver compressed air is mounted at the bottom of a centrally positioned, vertical air-lift pipe (geyser); it ensures that optimal contact between the compressed air and the barley occurs while it is submerged in the steep liquor. Oxygen supplied to the grain in this manner is preferable to delivery by nozzles mounted on pipes, since the entire content of the steeping vessel is recirculated. This conveniently takes place over the course of the entire wet steeping period.

Continuous removal of CO_2 during the air rests prevents any accumulation of the gas and likewise an increase in the temperature of the grain above 20–22 °C. As already mentioned, the air entering the steeping vessel must be attempered and conditioned, so that it is completely saturated. This helps prevent moisture from evaporating on the surface of the barley, especially in the uppermost stratum of the steeping barley. Evaporation would cool the top layer, while the middle and bottom layers would retain their original temperature, resulting in different conditions and thus uneven germination.

It may also be beneficial to spray the top layer of the grain for a very short time, i.e., only for a few seconds, to prevent this from occurring in smaller steeping vessels.

It is very important to control the temperatures in the steeping vessel and in the steeping grain itself (at different heights) and in some instances in the air drawn off by the CO_2 exhaust fan. The same applies to monitoring the moisture content at the individual steps of the steeping process. The simplest method is to bury a 1 kg linen sack of barley in the bed of steeping grain. Also, rapid methods for determining moisture are available (the carbide method or infrared drying).

A modern steeping process is carried out as follows:

First wet steep: with a liquor temperature of 12 °C until the grain reaches a moisture content of up to 30%; duration 4–6 h; intensive washing occurs through aeration, preferably with recirculation.

First air rest: 14–20 h, depending on the water sensitivity of the barley; CO_2 removal occurs at approximately 50 m^3/(t·h), first periodically and then continuously; the temperature must not exceed 20 °C.

Second wet steep: with a liquor temperature of 18 °C until the grain reaches a moisture content of 37–38%; duration 1–2 h; intense aeration is carried out, possibly through continuous recirculation.

Cast out for a maximum of 1–2 h; the total duration of steeping is 22–28 h.

If available, a flat-bottomed steep would be ideal as a second steeping vessel. It would allow the steeping process to continue after the first wet steep as follows:

Second air rest: at a temperature of 18 °C until uniform germination (chitting) occurs; CO_2 removal is constant at 100–150 m^3/(t·h).

Third wet steep: with a liquor temperature of 18 °C, a moisture content of up to 41% is reached; duration is 1–2 h.

Cast out for a maximum of 1–2 h, the total duration of steeping is 36–48 h, perhaps up to 52 h.

Since the temperature inevitably increases during the air rest, a corresponding modification to the following wet steep is necessary to avoid temperature shock, which can be harmful during the first 48 h of germination. A stepwise increase in temperature, in conjunction with a steep-out temperature of 18 °C, transitions into a germination process with falling temperatures (refer to Section 1.5.3.3). For this reason, it is also important that a sufficient volume of steep liquor at 18 °C is available for wet steeping. The shorter process with only two wet steeps offers the benefit that a favorable moisture content of 38% can be achieved by undergoing a second wet steep as well as by casting out wet. Furthermore, steep liquor is only needed for two wet steeping rests, thus reducing the required liquor volumes to 3–3.5 m^3/t. Additionally, when seasonal outdoor temperatures are warm, it is often difficult to maintain the desired temperatures in hopper-bottomed steeping vessels during the second air rest, i.e., the initial stage of germination. In this case, the critical phase would be more favorably carried out in the germination system under controlled conditions, if sufficient germination time is available (1 day for steeping and 6 days for germination).

The 2-day steeping process, the second day of which would ideally be accomplished in a flat-bottomed steep, offers the prospect of adding a third wet steep to raise the uniformly chitting grain to a moisture content of 41–42%. If the grain is cast out during the third wet steep, and given

optimal aeration, it is to be kept sufficiently brief that the germinating barley does not experience "water shock." Overcoming this condition in barley can take up to 12 h because the surfaces of the kernels must be dry. The film of steep liquor on the surface of the grain blocks the oxygen supply, temporarily inhibiting further germination and the formation of crucial enzymes. In this case, casting out dry is more favorable; however, there must be a sufficient period (3–4 h) between the third wet steep and the final transfer of the steeped barley to the germination vessel.

A third wet steep is considered more advantageous for barley possessing a steelier endosperm structure in order to achieve better and more uniform moisture penetration of the grain. Even with barley cultivated under hot and dry conditions exhibiting a low water sensitivity, it may be the case that the rapidly growing embryo deprives the endosperm of moisture or possibly even extracts moisture after it has been taken up by the endosperm.

When casting out wet, the additional pressure created by the pump may amplify the effects of the hydraulic pressure already present in the steep. This disadvantage can be alleviated by employing pipes of appropriate diameters and through the installation of two or more cast-out pumps. This enables several days' worth of germinating grain to be moved from steeping vessels situated on a lower level and transferred to germination vessels located on various higher levels, while minimizing the adverse effects of pressure on the grain.

1.3.6.3 Other Steeping Methods *Other methods*: based on the principles similar to the "pneumatic steeping method" described above, the process known as *flush steeping* aids in compensating for the temperature increase during the air rests through the introduction of several, in some instances, very short wet steeps.

Also introduced in the 1960s, the process of *resteeping* after a period of about 60–70 h of steeping and some germination allows for an additional full steeping process lasting 10–18 h to be performed with a liquor temperature of 18 °C and/or 12 °C. This elevates the original moisture content of 38% during germination to 50–52% in forking grain.

Both flush steeping and resteeping have contributed greatly to the knowledge of modern steeping technology; however, they are no longer implemented due to their high water consumption and the increased energy costs for drying the extremely moist green malt.

Spray steeping is carried out in the germination system either with or without an upstream steeping auger or steeping drum. The steep liquor is sprayed onto the grain by means of nozzles attached to the turner. In order to achieve a satisfactory level of homogeneity, the feed rate of the turner in the Saladin germination box (refer to Section 1.5.3.3) is slowed down initially, and the rotation rate of the turner augers is increased to as high as 36 rpm. The feed rate is accelerated, and the rotation rate is decreased only after the barley begins to chit. It is important that the intervals between the wet steeps and the air rests be maintained similar to the pneumatic steeping process to achieve the relevant physiological effect. In some instances, uniform moisture levels may not be achieved in harder grain.

1.3.6.4 Assessing Steeping Operations An *assessment of steeping operations* can no longer be carried out using only observation and practical experience, given the modern large steeping and germination facilities predominantly in use today. Precise measurement of the moisture content and the temperature during the individual stages is necessary (refer to Section 1.3.6.2). Moisture uptake can occur at different rates and is subject to the individual characteristics of the barley. During a 2-day steep, prior to raising the moisture content to above 38%, the barley must be examined to ensure that chitting is uniform throughout the grain. Further monitoring of the growth of the embryo, e.g., whether forking is homogeneous, allows conclusions to be made about the efficacy of the steeping process.

1.3.6.5 Steeping Losses *Steeping losses* comprise the following:

1. dust and impurities: approximately 0.1%
2. leaching of substances from the husks: approximately 0.8%
3. respiration, depending on the intensity of the steeping process: 0.5–1.5%; long air rests are associated with greater losses compared to those incurred through extended periods of wet steeping.

Floating barley is not considered a loss since it is collected and sold. In total, the losses amount to 0.1–1.0%.

1.3.6.6 Cleaning and Maintenance *Cleaning and maintenance* of the steeping equipment must be given particular attention due to potential contamination by the microorganisms present on barley. The coating on the inner surfaces of the

steeping vessels must be monitored and, if necessary, repaired or replaced. Iron steeping vessels risk deterioration in the quality of the malt. The more fittings are on the equipment, the more difficult it is to clean and maintain the vessels, though modern high-pressure sprayers can provide some assistance. In the case of round, flat-bottomed vessels, an automatic cleaning system both below and above the deck is essential.

1.4 Germination

1.4.1 The Theory of Germination

Germination is a physiological process in which the organs of the embryo, the rootlet, and acrospire develop by consuming the nutrients stored in the endosperm.

Germination takes place only under certain conditions: ample moisture, heat, and air, i.e., oxygen. The kernel only requires a moisture content of 35–40% to initiate the metabolic processes of germination. However, in order to convert the substances in the endosperm into those desired by maltsters within the time normally allotted for germination, a moisture content of 43–48%, even 50%, is necessary. The water required to activate and maintain the metabolism of the embryo is supplied in the process of steeping and by subsequent spraying. The primary task in properly managing the malting process at this stage is to maintain the moisture content at the appropriate level throughout the germination period. If the moisture content declines, the embryo's metabolic rate and therefore germination become compromised.

The most favorable *temperatures* for uniform germination are between 14 and 18 °C. Metabolic processes are slowed at lower temperatures. At higher temperatures, they accelerate, increasing losses through respiration.

The energy required for germination is furnished by the process of respiration; for this reason, atmospheric oxygen is vital for growth. The energy for fueling respiration is provided by carbohydrates, especially by starch. The products of respiration are heat, carbon dioxide, and water vapor. Carbon dioxide inhibits respiration; when there is a lack of oxygen, fermentation begins, and the metabolites resulting from this process form in the kernel. A sufficient amount of air must be supplied to ensure that respiration can take place normally, and therefore, CO_2 must also be removed. Conversely, excessive aeration must also be avoided, as this increases the respiratory losses. Thus, access to atmospheric oxygen may need to be somewhat restricted in the second half of germination.

By changing the factors influencing growth – moisture, temperature, oxygen, and time – the metabolic processes of germination can be regulated within certain limits.

Once the conditions of germination have been met, the grain begins to show perceptible signs of change externally. The root sheath or coleorhiza breaks through the grain, i.e., the barley "chits." This is followed by the emergence of the radicle and seminal rootlets from the grain; this is known as "forking." The coleoptile breaks through the pericarp and the testa, and the acrospire grows under the lemma toward the distal end of the kernel. Both sets of structures should only be allowed to develop to a limited extent during artificial germination in the malting process.

In addition to these outward manifestations of growth, the endosperm is also transformed: enzymes catabolize the substances stored as reserves and convert them into soluble molecules. These molecules either serve to generate energy, or they are employed in the formation of new tissues in the rootlets and the acrospire. These processes become visually perceptible as the friability of the endosperm increases.

Supplying the water that activates the metabolism of the embryo causes auxins (gibberellic acid and gibberellin A3) to be excreted. These are released by the embryo and move through the developing vascular system to the portion of the aleurone layer which abuts the scutellum. The auxins, which are not yet detectable in the grain after casting the steep, are present in a concentration of 46 µg/kg barley (dry matter) after 24 h, 50 µg after 48 h, and only 34 µg/kg barley after 72 h. Only 2–5 µg/kg can be detected in kilned malt if gibberellic acid has not been added (not permitted in Germany). The gibberellins in the aleurone layer and in the scutellum induce the *de novo* synthesis of a number of enzymes, such as α-amylase, limit dextrinase, and the endopeptidases. The formation of endo-β-glucanase, endoxylanase, and phosphatase is promoted by gibberellins. Additionally, activation of sulfhydryl endopeptidases as well as exoenzymes, such as β-amylase, various exopeptidases, and exo-β-glucanase, among others, occurs as a result of the degradation of protoplasmic bonds or the liberation of activating groups (e.g., sulfhydryl groups). The low molecular weight substances resulting from the catabolic activity of various enzymes are taken up by the scutellum and conveyed to the embryo. Due to the aforementioned vascular system, the formation of

enzymes and their subsequent effects on the kernel are more pronounced on the dorsal side than on the ventral side because it runs almost parallel to the epithelium.

The most important groups of hydrolases relevant here are the various proteolytic enzymes, the hemicellulases, the amylases, and the phosphatases. The enzymatic activities involving other substance groups are of less consequence for malting and brewing.

1.4.1.1 Cytolytic Enzymes *Cytolytic enzymes*: The *hemicellulases* or *cytases* comprise a number of enzymes, which can be classified according to the structures of the hemicelluloses as follows:

β-Glucanases: endo-β-1→4-glucanases, endo-β-1→3-glucanases, non-specific endo-β-glucanases, exo-β-glucanases, β-oligosaccharases, and β-glucan solubilase

Pentosanases: endoxylanases, exoxylanases, xylo-oligosaccharases, arabinosidases, feruloyl esterase, and xyloacetyl esterase

While the exoenzymes already exhibit a certain level of activity in the dormant grain, the formation of the endoenzymes (endo-β-glucanase and endoxylanase) is initiated at the onset of germination by auxins in the scutellum and aleurone layer. All of the endo-β-glucanases develop vigorously in the presence of sufficient amounts of oxygen. They break the soluble, high molecular weight β-glucans in the non-starch polysaccharides (gum substances) down into medium molecular weight glucan dextrins. The activity of exo-β-glucanases increases 10-fold, cleaving the β-1→4 bonds of glucan chains from the non-reducing end, giving rise to the disaccharide cellobiose. This disaccharide is similar to laminaribiose, a molecule also containing a β-1→3 bond, in that it is degraded by the corresponding oligosaccharases to form glucose. The high molecular weight hemicellulose β-glucans are linked to proteins by an ester bond and possess molecular weights of up to 40×10^6 Da. These are liberated by β-glucan solubilase and are thereby converted into soluble molecules. This enzyme, a carboxypeptidase, is present in the dormant grain prior to steeping; its activity is increased by a factor of 2 to 3 during germination. β-Glucans first become accessible to degradation by the β-glucanases described above through the catabolic activity of β-glucan solubilase (Table 1.1).

The high molecular weight araboxylans are degraded from the "inside" out by endoxylanases; the arabinosidases separate the arabinose side chains, thus facilitating the exoxylanase activity. The final products of the reactions are arabinose and xylose, which, like glucose, are utilized either to create new cells or for energy metabolism.

Feruloyl esterase also contributes to this process of degradation by breaking the ester bond between ferulic acid and arabinoxylan. However, there is also cross-linking between the arabinoxylans and ferulic acid, dehydrodiferulic acids, and proteins. The release of ferulic acid, which also takes place in the brewhouse during mashing, plays a particular role in the aroma of some types of beer (refer to Section 8.4.3).

Parallel to the enzymatic reactions involved in the degradation of β-glucans, xylan solubilase is also effective at catabolizing pentosans. It contributes to the release of high molecular weight araboxylan, which is then further broken down by xylanases and arabinosidase. A feruloyl esterase

Table 1.1 The influence of various malt parameters on the extract difference (EBC).

Moisture content (grain)	[%]	40	43	46	
Extract difference (EBC)	[%]	5.1	2.9	1.1	
Viscosity	[mPa·s]	1.69	1.6	1.52	
Germination temperature	[°C]	13	15	17	
Extract difference (EBC)	[%]	1.6	1.4	1.0	
Viscosity	[mPa·s]	1.55	1.52	1.55	
Germination period	[d]	4	5	6	7
Extract difference (EBC)	[%]	3.6	2.0	1.5	1.2
Viscosity	[mPa·s]	1.65	1.59	1.54	1.48
CO_2 concentration after 3 days of germination	[%]	0	10	20	
Extract difference (EBC)	[%]	0.7	1.2	1.7	
Viscosity	[mPa·s]	1.47	1.48	1.51	

is also effective in these degradation processes: it breaks the bonds between araboxylan molecules and ferulic acid.

Little research has been done on pentosan degradation in the malting process, but it appears to subject to the same factors involved in the degradation of β-glucans. Pentosans are of far greater significance in the process of malting wheat, since the viscosity of wheat wort is primarily influenced by pentosans. This area still requires additional research.

For assessing cell wall degradation in barley malt, the global methods, for example extract difference and the viscosity of the Congress wort, have been deemed as less informative than specific analyses focusing on cell wall degradation, such as the Calcofluor method. It determines the modification (degradation) "M" and the homogeneity "H," where "M" should be at least 85% and "H" at least 75% for well-modified malts. Higher values can be achieved with barley malt produced from a single variety as well as friabilimeter values above 90%.

The impact of the glucanases is much more pronounced than that of the pentosanases. Cytolytic degradation during germination comprises 4/5 of the glucans and only 1/5 of the pentosans. The cell walls are not completely disintegrated; rather, only individual groups are removed, making the cell walls more permeable. The process of modification progresses gradually, making its way along the kernel parallel to the epithelium, from the proximal end, where the embryo is located, to the distal end of the kernel. The degree of modification of the malt is determined using the following methods: during germination, the chalkiness of the endosperm is determined. In the finished malt, the friability is analytically evaluated (grain sectioning); the friabilimeter value according to Chapon records the friable, half-glassy, and completely glass kernels (Table 1.2). The finished malt can also be stained with calcofluor or methylene blue after longitudinally sectioning the kernel (e.g., by cutting), which likewise determines the modification and homogeneity. As part of the Congress analysis, the difference in extract yield between the finely and coarsely ground malt as well as the viscosity of the wort can be measured. Modification can be positively influenced by a high moisture content and a temperature reaching approximately 18 °C in the germinating grain, including an ample supply of oxygen and a germination period that is appropriate under those conditions. In certain circumstances, higher germination temperatures can result in a more pronounced modification gradient between the embryo, at the proximal end, and the distal end of the kernel. This manifests itself in the somewhat higher viscosity of the 17 °C sample. A high moisture content may compensate for other factors (e.g., high temperature and longer germination period), as the overview in Section 1.4.1.1 explains; however, protein modification must also be considered.

The friabilimeter data (Table 1.2) show a similar tendency regarding the effect of the germination conditions on cytolytic modification.

A comparison of the viscosity and the β-glucan content between the Congress wort and the 65 °C wort provides excellent information (refer to Section 1.8.3) about modification. When comparing both worts, a sufficiently and homogeneously modified malt exhibits a viscosity of 1.48/1.55 mPa·s and a β-glucan content of 140/220 mg/l. Worts from unevenly modified malt exhibit values of 1.54/1.68 mPa·s and 230/440 mg/l, which can lead to problems with standard mashing procedures in the brewhouse and with subsequent filtration of the beer. Barley with damaged embryos, e.g., ungerminated kernels (lie-backs) and those that are unevenly germinated, exhibit poor friability, a correspondingly high proportion of completely glassy kernels, and a poor level of homogeneity with reference to modification. When these malts eventually enter the brewhouse and the process of mashing, the β-glucan solubilase activity introduces a significant amount of high molecular weight β-glucans which cannot be degraded to an adequate extent by the temperature-sensitive endo-β-glucanases. This results in difficulties during lautering and filtration (refer to Section 7.7.1).

Table 1.2 The influence of various malt parameters on the friability of the malt.

Moisture content (grain)	[%]	38	42	43.5	45
Friabilimeter friable/completely glassy	[%]	58/3.3	85/1.0	90/0.8	93/0.5
Germination temperature	[°C]	14.5	16	18	
Friabilimeter friable/completely glassy	[%]	90/0.8	94/0.4	93/0.5	
Germination period	[d]	5	6	7	8
Friabilimeter friable/completely glassy	[%]	80/3.0	85/1.3	90/0.8	95/0.3

1.4.1.2 Protein Degradation *Protein degradation* is carried out by a set of proteolytic enzymes, which can generally be divided as follows:

Endopeptidases (proteinases) catabolize true proteins, and through their activity create high molecular weight degradation products, such as macro- and polypeptides. As the activity of the endopeptidases continues, oligo- and dipeptides are produced as well. Should the process be allowed to advance even further, protein degradation will eventually extend to the amino acid level. There are a large number of endopeptidases, since these enzymes are very specific about where they bind to cleave the peptide chain. The enzymes are defined by the type of amino acid residues created as a result of their activity.

Exopeptidases approach the peptide chains from the outside and break off individual amino acids from large protein molecules. Carboxypeptidases cleave amino acids from proteins at their carboxy terminus, while aminopeptidases hydrolyze the bonds of proteins at their amino terminus. The dipeptidases, by contrast, do not evince this kind of specificity for either group.

A number of the proteolytic enzymes are already detectable in ungerminated barley. Depending on the conditions during germination, their activity can increase to be several times the initial value.

Protein degradation occurs schematically as depicted in Figure 1.1.

The degree of catabolism is different according to whether certain conditions have been met during malting; for instance, degradation during malting can produce more high molecular weight molecules or more amino acids. Since each of these groups of proteins is important for the quality of the subsequent beer, protein degradation should neither be too extensive nor too limited in scope. Amino acids are crucial for the nutrition of the yeast, while the higher molecular weight polypeptides are central to body and foam formation in the finished beer.

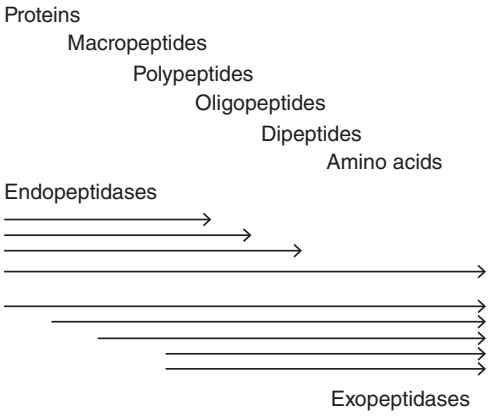

Figure 1.1 Protein degradation.

In order to evaluate the degree of protein degradation, the amount of soluble nitrogen must first be determined, which is expressed as a percentage of the total nitrogen (Kolbach index). The percentage of soluble nitrogen varies with the nitrogen content of the malt, ranging from 30% to 50% of the total nitrogen. A Kolbach index of 38–42% is favorable, given a total protein content of 10–10.5%. The amount of soluble nitrogen, based on 100 g of malt (dry matter), is normally between 600 and 700 mg. The soluble protein can be further categorized according to precipitation reactions or other methods of analysis (refer to Table 1.3).

The reserve proteins in the cells under the aleurone layer are subject to protein degradation. This is the primary source for the water-soluble proteinaceous substances that supply the embryo with nutrients. With standard malting procedures,

Table 1.3 The percentages of soluble nitrogen in the malt according to molecular weight.

	Soluble N 600–700 mg/100 g malt (dry matter)	
Molecular weight		
High	Medium	Low
20%	20%	60%
Of this, around 33% coagulable N		Of this, around 60% titratable with formol, and around 35% is α-amino N

the histological protein is only degraded to the extent necessary to reach optimal modification. The gluten remains almost untouched and is found virtually unchanged in the spent grain.

True proteins are catabolized to a greater or lesser extent by the proteolytic enzymes. Though the albumins and globulins initially diminish, they increase toward the end of germination. The prolamins (hordein) first decrease gradually and then are rapidly and steadily degraded to approximately 40% of their original value. Glutelin degradation follows a similar pattern; however, toward the end of germination, the glutelins are resynthesized from low molecular weight substances. The products of protein degradation increase to the same extent as the true proteins decrease. Protein Z, which belongs to the albumins, and the lipid transfer protein I are only slightly degraded during germination. Both are significant because they promote foam formation in addition to playing a role in the development of haze. The total soluble nitrogen increases rapidly in the first days of germination, especially if the temperature is high at the beginning of the process. The soluble nitrogen normally reaches a maximum value after 4–5 days but can be boosted if conditions during germination allow it. The concentration of amino acids also increases steadily. However, the amino acids will decline if germination is prolonged. The amino acids are employed to generate predominantly insoluble proteins, so that a reduction in the amino acids is observed toward the end of germination. After 4–6 days, a state of equilibrium between the catabolic and anabolic processes develops, which is only apparent as a shift in the fractions of proteinaceous substances. This equilibrium can be influenced by the conditions present during germination (Table 1.4). Table 1.5 provides an overview of the changes in the α-amino acids over the course of germination. A high level of protein modification results in the high molecular weight protein fractions increasing in absolute terms, although their overall percentage decreases under the following conditions: a high moisture content in the germinating grain, low temperatures, and an optimal germination period. The quantity of low molecular weight nitrogen always increases. This ratio can change at high germination temperatures. Alternative malting procedures, such as a resteeping step, can result in a different ratio of high to low molecular weight proteins.

The overall quality and character of the barley as well as the protein content and the qualitative composition of the proteinaceous substances also have some effect on protein modification. Barley with a high protein content usually exhibits a lower degree of protein modification than barley containing less protein under identical malting conditions. Even though no clear relationship exists between proteolysis and cytolysis in the

Table 1.4 The influence of various malt parameters on the Kolbach index, i.e., the degree of protein modification.

Moisture content (grain)	[%]	40	43	46	
Kolbach index	[%]	39.5	43.9	46.1	
Germination temperature	[°C]	13	15	17	
Kolbach index	[%]	44.9	43.9	41.9	
Germination period	[d]	4	5	6	7
Kolbach index	[%]	35.4	38.8	39.8	40.9
CO_2 concentration after 3 days of germination	[%]	0	10	20	
Kolbach index	[%]	40.9	38	42.8	

Table 1.5 The influence of various malt parameters on the α-amino nitrogen content of the malt.

Moisture content (grain)	[%]	39	42	45	48	
α-Amino nitrogen	[mg/100 g (d.m.)]	105	112	136	175	
Germination temperature	[°C]	12	15	18		
α-Amino nitrogen	[mg/100 g (d.m.)]	150	132	120		
Germination period	[d]	4	5	6	7	8
α-Amino nitrogen	[mg/100 g (d.m.)]	125	128	135	145	142
CO_2 concentration after 3 d of germination	[%]	0	10	20		
α-Amino nitrogen	[mg/100 g (d.m.)]	134	140	159		

kernel, a certain amount of proteolysis must precede cytolytic modification to achieve the desired level of endosperm friability. The variety, provenance, level of maturity, and homogeneity of a barley lot also have an impact on the circumstances under which protein modification takes place. The protein content of barley decreases somewhat as a result of germination, since the rootlets, and the protein in them, are removed after kilning. While approximately 10% of the protein in a barley kernel is located in the rootlets, the protein content of the malt compared to barley is only 0.2–0.5% less, since losses of other substances occur as a consequence of respiration over the same period.

Comprehensively characterizing protein degradation by measuring the soluble nitrogen or the α-amino N (FAN) content of the malt does not yield specific information about the proportion of individual amino acids, such as leucine, isoleucine, and valine, which are vital constituents for fermentation. Experimental trials in less-modified malt (resulting from a low moisture content) have shown that these amino acids are present in low absolute quantities and also in their relative proportions. Higher germination temperatures (18–21 °C) produce the same result.

A decline in foam formation and head retention is not expected from malt with a high level of cytolytic modification. And yet, an extremely high level of proteolysis, for instance, in malt with a markedly elevated Kolbach index accompanied by a disproportionately high FAN content, can negatively affect foam.

For years, new barley varieties have revealed a tendency toward increasingly higher levels of protein modification, which has had an unfavorable effect on beer foam. Thus, the Kolbach index in malt specifications has often been limited at the upper end, ordinarily to 40–41%. However, in this same malt, there has been demand among brewers for the attributes characterizing the degree of cytolytic modification to remain the same, and the new barley varieties, for the most part, have exhibited very favorable levels of cytolysis. This is nevertheless the limiting factor in efforts, for instance, to reduce the length of the germination period during malting. In order to restrict the degree of protein modification while at the same time attempting to facilitate thorough cytolytic degradation, higher germination temperatures, e.g., at 18 °C, are applied with the same moisture content in the germinating grain (44–45%). If the barley germinates evenly, curtailing the germination period from 6 to 5 days may be feasible. The higher germination temperature will undoubtedly cause correspondingly higher malting losses. The ratio of FAN to soluble N is a reliable tool for monitoring how uniformly modification is advancing. It should be around 20–21%. A warm, short germination period can result in this ratio declining to 17–18.5%, which may give rise to problems during fermentation and maturation in the brewery.

The same applies to *S*-methylmethionine, the precursor of dimethyl sulfide. When quantifying the concentrations of the α-amino acids, the equally important cyclic amino acid, proline, is not measured. Proline is present in the Congress wort in quantities ranging from 300 to 500 mg/l, depending on the barley variety, cultivation region (lower in Continental barley than in maritime barley), and the degree of modification.

The amines generated by the enzymatic decarboxylation of certain amino acids, e.g., histamine from the amino acid histidine, tyramine from tyrosine, and tryptamine from tryptophan, are also of great importance for the physiological significance of the growing embryo. Additionally, hordenine is formed through the addition of two methyl groups to tyramine, and likewise, gramine from tryptamine. The increase in amines during malting generally parallels the degree of protein modification, which is fostered by a high moisture content in the grain during germination, by higher or, less so, falling germination temperatures as well as by a longer germination period. Hordenine and gramine are present in large quantities in the rootlets and in the acrospire and also in the malt. They both play a role as precursors for the nitrosamines that are formed during kilning (refer to Section 1.6.1.2).

1.4.1.3 Phosphate Degradation *Degradation of the phosphates*: The phosphatases, which exhibit enzymatic activity during germination, cleave phosphoric acid and its acidic salts (primary phosphates) from an ester-like bond with organic substances. While only 20% of the phosphates exist in an inorganic form in barley, approximately 40% occur in this form in malt. This increases the titratable acidity, above all, the acidity already present in the kernel. The buffering capacity increases significantly, which is important in maintaining a pH in the grain of around 6.0. Moreover, a number of organic acids are formed as intermediate metabolic products likewise through deamination of the amino acids or through oxidation of the sulfurous amino acids.

1.4.1.4 Starch Degradation *Starch degradation*: The amylases degrade the native starch into maltose. The enzymes are distinguished as follows:

- α-Amylase, known as endoamylase or dextrinogenic amylase as well
- β-Amylase, also called exoamylase or saccharogenic amylase

β-Amylase approaches the molecules amylose and amylopectin from the outside, cleaving individual maltose units off them. α-Amylase, by contrast, attacks both of these molecules from the inside. The fragments broken off of the amylose molecules are approximately six glucose units in length (oligodextrins), while those originating from amylopectin may contain one or more branches. β-Amylase then has access to positions on these side chains where it can release more maltose. α-Amylase can also degrade higher molecular weight dextrins; however, both enzymes can only cleave α-1→4 bonds, so that even after prolonged exposure under optimal conditions, only about 80% of the starch is degraded, yielding maltose, maltotriose, and glucose. The remaining fragments are present in the form of limit dextrins, which possess α-1→6 bonds.

The α-1→6 bonds can be cleaved by the limit dextrinases to form linear dextrins, which are then subject to further degradation by the amylases. Maltose can be further degraded by maltase to glucose. Sucrose is utilized by plants as a means to transport carbon and can be split into glucose and fructose by the enzyme invertase.

β-Amylase is already present in its active form in the dormant grain. However, for the most part, latent β-amylase is converted to its active form during germination. This can be triggered by activators, the degradation of inhibitors, or its release from protoplasmic bonds, converting it to the active form.

β-Amylase develops most favorably at a moderate moisture content, reaching its maximum on the fifth day of germination. The level of the enzyme increases at higher concentrations of carbon dioxide in the air, while higher germination temperatures result in lower levels of β-amylase (Table 1.6). With the last two parameters, the same applies to the degree of protein modification.

α-Amylase is not detectable in barley. Its formation is induced at the beginning of germination by auxins in the scutellum and aleurone layer. α-Amylase is generated from amino acids.

During germination, the activity of neither amylase is at full capacity. The most crucial function of germination is the release and activation of β-amylase and the formation of α-amylase. Without the action of the latter, saccharification cannot be completed during mashing. The principal activity of the two amylases only fully comes to fruition in the brewhouse during the mashing process when they degrade the starch into sugars and dextrins.

Cytolysis and proteolysis are monitored by means of the physical and chemical attributes of the Congress wort or of the liquid extracted from a malt sample. However, the time required for saccharification of the Congress mash and the limit of attenuation of the same wort occasionally provide less-than-reliable information about the state of the cytolytic and proteolytic modification in malt. The activity of the amylases is determined directly in experimental trials with various barley varieties, at

Table 1.6 The influence of various malt parameters on the α- and β-amylase contents of the malt.

Moisture content (grain)	[%]		40	43	46
α-Amylase	[ASBC]		58	63	92
β-Amylase	[°WK]		322	366	361
Germination temperature*	[°C]		13	15	17
α-Amylase	[ASBC]		68	69	62
β-Amylase	[°WK]		251	263	230
Germination period	[d]	1	3	5	7
α-Amylase	[ASBC]	0	24	50	63
β-Amylase	[°WK]	120	247	347	366
CO_2 concentration after 3 d of germination	[%]		0	10	20
α-Amylase	[ASBC]		74	65	62
β-Amylase	[°WK]		316	320	331

*Values measured in kilned malt.

the beginning of a new harvest, or with particularly enzyme-rich malts. The cumulative effect of these enzymes is determined by the analysis "diastatic power" (DP). The α-amylase activity is determined according to the EBC method, while β-amylase is calculated as the difference between the DP and α-amylase as follows: DP – 1.2 × α-amylase.

α-Amylase can only be synthesized in the presence of oxygen. Its synthesis is stimulated by a high, gradually increasing moisture content and by an initially higher, then falling germination temperature as well as by a longer germination period. If carbon dioxide accumulates in the air as germination progresses, the curve marking the development of α-amylase begins to flatten.

By contrast, β-amylase, as an exoenzyme, reacts less dramatically to the factors positively or negatively affecting germination. It also reaches its maximum earlier than α-amylase.

The amount of β-amylase originally present in barley varies between 60 and 150 units and depends on certain attributes of the barley (variety, provenance, and growth conditions). Similarly, synthesis of both amylases is determined by qualities inherent to the barley. The conditions under which germination is conducted influence the amount of the amylases in the green malt as follows (see above):

When the malt is kilned, a portion of the amylases perish. β-Amylase is more sensitive to high temperatures than α-amylase.

The amylase activity first begins close to the embryo and progresses with the growth of the embryo parallel to the epithelium. The starch grains bordering on the scutellum are gradually converted into various sugars for consumption by the embryo. The loss of starch remains low in the first few days of germination but increases as germination progresses to reach a value of approximately 5%.

The factors affecting germination do not impact the gelatinization temperature of the starch to any great degree. Starch gelatinization is an important factor during the mashing process with regard to starch degradation. The following conditions positively, though only slightly, influence the gelatinization temperature:

Steeping and germinating for 7 days with a mean moisture content of 42–44% has the most favorable effect. The temperature during germination within its usual range of 14–18 °C hardly impacts the gelatinization temperature.

1.4.1.5 Lipid Degradation *Lipid degradation*: lipases break the ester bonds between glycerin and fatty acids. According to recent research, these enzymes are not detectable in dormant grain. Their activity can be influenced by the germination parameters. They originate at the scutellum during germination and spread in a line parallel to it until they reach the distal end of the grain. Of the fatty acids released through hydrolysis, linoleic acid and linolenic acid are both converted into their hydroperoxides by lipoxygenases. Lipoxygenase I is already present in dormant barley, while lipoxygenase II is first formed during germination. Both are largely inactivated during kilning. Lipoxygenase I produces 9-linoleic acid hydroperoxide from linoleic acid, while lipoxygenase II creates 13-linoleic acid hydroperoxide. These are both converted into (*E*,*Z*)-2,6-nonadienal via a hydroperoxide lyase. This compound is the primary component of the cucumber aroma perceptible in green malt. Furthermore, other substances, such as hexanal and (*E*,*E*)- or (*E*,*Z*)-2,4-decadienal, are generated. Similar to the numerous other alkanals, alkenals, and alkanedienals as well as alcohols (e.g., hexanol-1) created in the production process, they contribute to the flavors and aromas of malt, wort, and beer, especially in aged beer (refer to Section 7.6.5.3).

As a result of catabolic and anabolic processes, the crude fat content of the barley compared to the malt drops by 20–27%, and the composition of the triglycerides shifts toward polyunsaturated fatty acids. Fat is required to produce the rootlets; the amount varies from 1.04% to 1.25% according to variety. However, the majority of the fat in the barley remains in the aleurone layer. Barley grown under dry conditions contains more lipids, which are also subject to more degradation. This kind of barley tends to generate more heat during germination.

The accumulation of carbon dioxide in the air to a concentration of 3–4% is favorable for germination. This is the case in floor malting, when the grain rests in the interval between turnings. Carbon dioxide inhibits lipoxygenase activity. CO_2 levels can be increased by recirculating air in a sealed germination box without impacting the activity of other enzymes or their degradation processes. Analytical data indicate that this is advantageous for the flavor stability of beer.

1.4.1.6 Polyphenol Degradation *Polyphenols* are found in the husks and also in the aleurone layer and in the reserve protein. They can, in part, be removed in the process of steeping, but the absolute changes are small. Polyphenols located in the endosperm become solubilized as other

groups of substances are degraded, e.g., proteins. This continues through the mashing process. The anthocyanogens increase to a greater extent than the polyphenols as a whole. The same is true of the group known as tannoids (600–3000 Da). The degradation of all of the polyphenol fractions parallels protein modification and flourishes under the same conditions during germination, which are known to be as follows: a high moisture content, a moderate or falling temperature, and an elevated CO_2 concentration in the air.

The polyphenol content and their individual fractions are heavily influenced by the oxidase systems that are active during germination, such as catalases, peroxidases, and polyphenol oxidases. The formation of these enzymes increases as malting rises in intensity (refer to Section 1.4.1.5). They are able to oxidize polyphenols in addition to the formation of keto groups, resulting in an increase in the size of the molecules.

1.4.1.7 Other Degradation Processes In addition to hydrolytic enzymes, barley also contains enzymes involved in plant metabolism, which possess different properties than the hydrolytic enzymes. Under aerobic conditions, these enzymes produce the lowest molecular weight degradation products, such as water and carbon dioxide, after they have been through various intermediate stages. Unlike hydrolytic cleavage, considerable amounts of energy are released in the process. If there is a lack of oxygen, however, anaerobic processes take place that yield less energy, e.g., fermentation (refer to Section 3.2.1).

1.4.1.8 The Growth of Microbial Flora During Malting *The growth of microbial flora during malting*: microorganisms occur naturally on malting grains and comprise bacteria, yeast, and other fungi. They thrive under the conditions present during malting, which provide them with nutrients as well as agreeable temperatures and moisture levels. Moreover, these microorganisms are present throughout the malting facility itself: in the steeping tanks, germination vessels, and conveyor systems, especially in any equipment used for transporting green malt to the kiln.

Strict monitoring of the barley received and maintaining the health of the embryos in the kernels are a fundamental part of storing barley, e.g., through drying, cleaning, and dust removal as well as the cleaning and maintenance of the equipment.

Naturally occurring microorganisms include lactic acid bacteria, yeasts, and, above all, molds (refer to Section 1.2.6). In spite of the fact that the grain is washed during steeping (sometimes for a very short time), the microorganisms are nevertheless capable of a considerable amount of growth during the air rests, subsequently during germination, and even at the lower temperatures applied during withering in the kiln. The microorganisms not only develop on the surface of the grain, where they form biofilms, the molds, for instance, can even degrade certain constituents in the grain using their enzyme systems (proteases, β-glucanases, xylanases, and even cellulases), thus contributing to "modification." However, this is beyond the control of the maltster. Should the grain be heavily contaminated with mold of the genus *Fusarium*, excessive yet irregular cytolytic degradation of the endosperm as well as extreme proteolysis and premature starch degradation can occur. In doing so, hydrophobins, substances that can incite gushing, and mycotoxins are generated, which severely compromise the quality of the malt. The metabolic products of these microorganisms can also give off a stale, musty smell that is still perceptible far downstream in the process through to the finished beer. Problems of this kind can be counteracted by proper treatment of the barley, intensive washing in the steeping vessel, and careful cleaning of the malting equipment.

1.4.2 The Practice of Germination

It is the task of the maltster to oversee and guide these complicated processes, so that the substances in the kernels change in the desired manner and are subsequently present in the correct composition. Maltsters can deduce how well germination is progressing, based on the following indicators:

1. *Physical appearance of the kernels*: development of the rootlets and acrospire as well as the progressive "softening" of the endosperm.
2. *The resultant metabolic products*: water vapor generated by respiration, the formation of carbon dioxide, and heat in the piece over a certain time period.

In traditional floor malting, the accumulation of heat in the piece was measured using a thermometer; all of the other changes in the grain were judged according to the maltster's experience, for instance, in how the kernels looked and felt. In modern, large-scale pneumatic malting facilities, the levels of moisture and carbon dioxide have to be measured precisely in order to properly control germination. This is carried out in addition to assessing how the changes are physically manifested in the individual kernels. The primary issue with malting unquestionably comes down to the following: to

what extent can or should artificial germination be allowed to advance? Maltsters do not want to cultivate new plants. On the contrary, their objective is to promote the transformations in the kernels required to generate the attributes desirable in the type of malt they produce. Of course, the consumption of energy and materials should also be kept low. The gauge for every stage of development is the growth of the rootlets and acrospire as well as the modification of the endosperm.

1.4.2.1 Rootlets The *rootlets* are assessed according to their length. If they are as long as the grain, then the rootlets are considered to be "short." If they are 2–2½ times the length of the kernel, then they are deemed "long." The uniformity of their growth is of great significance, since it allows conclusions to be drawn about how well managed the germination process has been. This provides clues not only about the character of the barley but also the uniformity of the degradation processes in general. The rootlets of a piece germinated slowly at a lower temperature are compact and spiral in form. A piece subjected to rapid growth at warmer temperatures exhibits rootlets that appear thin and thread-like. These kinds of rootlets wither easily during kilning. In pneumatic malting facilities, the rootlets are weaker and are usually longer than those produced with floor malting. Strong rootlets indicate that more protein has been extracted from the kernel. The rootlets fall off during drying and cleaning and are subsequently sold as malt culms. The steps in the malting process should be carried out according to the individual stages of rootlet growth. For instance, the moisture content in the grain should only be increased to above 38–40% if all kernels capable of germination have chitted evenly. Likewise, consistent forking of the rootlets allows for further steps to be taken, such as increasing the moisture content, resteeping, and lowering or raising the temperature.

The rootlets do not grow as vigorously if the piece is particularly cold, is under an atmosphere heavy with CO_2, or when the piece has been resteeped. Rootlet growth can be suppressed to a considerable extent by resteeping for an extended period or with warm steep liquor. Conversely, rootlet growth is stimulated by warm, moist germination conditions and by leaving the piece undisturbed for longer periods.

Rootlets do not develop at all on non-germinating kernels. The barley is therefore considered to be an adjunct and not malt. Kernels also fail to germinate with improperly implemented or overly intense steeping procedures.

A high moisture content, allowing the piece to go undisturbed for too long or unevenly turning the piece, can stimulate excessive growth of the rootlets. The piece begins "felting" when small or perhaps even large clumps of green malt become matted together by intertwining rootlets. The consequences are uneven modification and a deepening of the color. Occasionally, rootlets are broken off through friction or severely damaged by improperly casting the steep using a pump. Furthermore, rootlets of the chitting or even forking grain can be inadvertently dislodged or disarticulated by a defective (Saladin) turning device during germination. Injured roots, as well as the malting of overly mature barley, lead to excessive acrospire growth.

In order to understand the process of growth in the kernel, maltsters should determine the percentage of chitting, forking, or ungerminated grains and record it on a daily basis. The same applies to the development of the acrospire (huzzars or bolters, see below).

1.4.2.2 Acrospire Development The length of the kernel also serves as a means to gauge *acrospire development*. Acrospire length is classified as 0, ¼, ½, ¾, 1, and greater than 1, depending on whether the acrospire has reached half, three-quarters, etc. of the kernel length. With lighter-colored malt, the acrospire does not reach quite the length that it does with darker malt. In modern malting systems, the acrospire length for lighter-colored malt is 0.7 on average with 75% of the piece reaching ¾ of the length of the kernel. With darker malt, however, 75% of the piece should exhibit an acrospire length between ¾ and 1. Since the acrospire is still visible in the kilned malt, it represents a valuable reference point about the uniformity of germination. The acrospire only provides reliable data regarding modification if the piece is germinated under cold conditions that favor slow growth. In addition to the length, the uniformity of acrospire development across the piece is of particular interest. When the acrospires vary in length, the barley may have been inadequately sorted, may represent a mixed lot of grain, or may have grown unevenly in the field. If the moisture content of the grain is increased too early during germination and is carried out under warm conditions, these factors can lead to a strong but varied acrospire development. Should the acrospire grow until it extends beyond the length of the grain, one speaks of the formation of "huzzars." This can occur with a high moisture content, the accumulation of condensate on the surface of the grain,

warm conditions during germination, or when the germination period is unduly long. Huzzars point to an unnecessary consumption of energy and material; with darker malt, a certain percentage of huzzars (5–10%) is nevertheless normal. With lighter-colored malt, huzzars serve as an indication that germination proceeded beyond the time required. The acrospire, similar to the rootlets, can also be influenced through artificial means. They are not completely independent of one another. By turning the piece more frequently, especially by spraying, acrospire growth is stimulated. CO_2 enrichment in the air and longer steeping periods suppress growth. Malt from Saladin germination boxes, especially when the moisture content of the grain rises in several stages, consistently tends to exhibit stronger acrospire development. The formation of huzzars under otherwise identical conditions is a function of barley variety. In general, however, huzzars can hardly be avoided at a moisture content of 50–52% during germination. Injured kernels often possess acrospires that grow perpendicular to the long axis of the grain.

Measures taken in the last third of germination period to improve malt modification should only be carried out after first assessing the growth of the acrospire. This helps avoid the formation of huzzars. These measures include spraying or increasing the temperature of the piece.

1.4.2.3 Modification of the Barley Kernel The *modification of the kernel* can be monitored by measuring the friability of the endosperm as it increases. Modification begins near the embryo and progresses parallel to the epithelium, spreading toward the distal end of the grain. The dorsal side of the kernel, where the acrospire develops, is modified slightly faster than the ventral side. Thus, there are inherent differences in the capacity for discrete segments of the kernel to undergo modification. For this reason, the modification of the endosperm cannot be accelerated arbitrarily. If the hemicellulase activity increases, e.g., by sustaining higher germination temperatures, enzyme activity does, in fact, increase at the proximal end of the kernel. However, the distal end of the grain does not experience modification more rapidly or more thoroughly. Instead, the difference in the modification level between proximal and distal ends shifts to favor the former even more. Under these circumstances, there would also be no correlation between the development of the embryo and the modification of the endosperm. While the acrospire and rootlets grow rapidly and strongly, modification of the endosperm lags behind. If, however, germination is carried out under an atmosphere containing some carbon dioxide during the modification phase or even if the piece is subjected to resteeping, the modification process exhibits a more favorable progression than would be expected solely on the basis of the growth of the embryo.

The capacity for modification in barley can differ. Barley low in protein as well as barley harvested in wet crop years or from maritime regions undergoes modification more rapidly and to a greater extent than protein-rich barley grown under dry conditions. Larger kernels require more intense germination conditions than smaller kernels; however, the capacity for modification is strongly dependent on the individual barley variety.

Barley modification must be assessed according to the type of malt to be produced. Although lighter-colored malts should possess a good, uniform level of modification, this is often limited in order to achieve the "light" target color, as opposed to dark malts. In the production of dark malts, a more extensive degree of modification is considered desirable for the formation of substances that provide color and aroma. If a malt is not sufficiently modified to fulfill the specifications, it is described as undermodified. Conversely, if the malt has undergone excessive modification, it is considered to be overmodified. A less-than-optimal friability, low enzymatic activity, and normally a short growth period are characteristics that cause modification to be lacking. In the brewhouse, undermodified malt does not achieve saccharification (conversion) as quickly, it results in a lower limit of attenuation, is more difficult to lauter, and likewise delivers only moderate yields. Fermentation may also be negatively impacted due to a deficiency in amino acids. Overmodified malt exhibits a completely friable endosperm, a high level of enzyme activity, and a very extensive degree of protein degradation. Even if the brewing process progresses smoothly, beer made with overmodified malt has an empty, harsh flavor and poor foam stability. Although it is very difficult to compensate for overmodification in the brewhouse, it is possible to offset undermodified malt somewhat by employing a more intense mashing regime. Excessively high temperatures and extended germination periods produce overmodified malt, while undermodified malt is the result of germination which is overly dry, too short, or carried out at temperatures that are too low. Both phenomena may be observed in barley that did not germinate uniformly, depending on whether germination was allowed to advance without waiting for the slower germinating kernels

to make progress, or whether a normal level of modification was expected to be achieved in these kernels. This is generally evidenced by a deviation in the values determined for the extract difference and viscosity. The friabilimeter value will also not be satisfactory, and the percentage of total glassy kernels will be too high.

Modification of the endosperm that appears oily or undefined is an indication that mistakes were made during malting. This can result from excessive spraying, but it is particularly associated with oxygen deprivation (intramolecular respiration). Such kernels are dark in color with a hard consistency in kilned malt.

The degree of modification can be determined by mechanical analysis methods, such as by sectioning kernels, the sinker test, and friability according to Brabender or Chapon. Staining methods (calcofluor and methylene blue) not only show the modified areas in the individual kernels, but they also allow the homogeneity to be calculated, thus providing valuable insight into the uniformity of the lot of barley being malted. Of the various physico-chemical methods available, cytolysis is best determined by the extract difference between coarse and fine-grind grist and the viscosity of the Congress wort. For proteolysis, the Kolbach index and the amount of soluble nitrogen are essential analysis methods. The Hartong–Kretschmer four-mash method at 20, 45, 65, and 80 °C can be used to draw conclusions about the modification and enzymatic power of malt, particularly the VZ 45 °C analysis (refer to Section 1.8.3).

1.4.2.4 Metabolism During Germination *Metabolism during germination*: the kernel draws its energy for germination from the respiration of starch and fat, converting it to carbon dioxide and water. Among other things, the heat liberated as a result of metabolism increases the temperature in the germinating grain (Table 1.7).

The losses incurred during malting are 8% (dry matter) under normal circumstances (refer to Section 1.7.2), which corresponds to approximately 4.5% of the grain being utilized in respiration. Of this, 4.2% is starch (calorific value, 17,300 kJ/kg (4140 kcal/kg)) and 0.3% fat (calorific value, 39,300 kJ/kg (9400 kcal/kg). Therefore, the germination of one metric ton of barley generates and liberates 845,000 kJ of heat energy (202,100 kcal). In addition, 68 kg of carbon dioxide and 28 kg of water are produced by respiration.

This amount of heat can serve as orientation for dimensioning cooling surfaces in germination vessels (refer to Section 1.5.2.8). The following quantities of heat energy are liberated over the course of an 8-day conventional germination regime per metric ton and hour (refer to Table 1.7).

In modern malting practices, germination begins during the steeping process. For this reason, in the previous example, the heat generated during the first and second day of germination has already been removed from the steep (refer to Section 1.3.5.8). If the figures for malting losses are approximately the same, a shorter germination period results in a greater accumulation of heat, which can be as much as 9600 kJ/(t·h) (2300 kcal/(t·h)). Moreover, the application of growth-enhancing substances (refer to Section 1.5.3.9) can cause considerable spikes in heat generation.

1.4.2.5 Germination Conditions *Germination conditions*: growth and modification are dependent on the *germination conditions*. The *temperature maintained during germination* defines it as either a *cold* or *warm* regime. The cold regime begins at 12 °C and climbs to 16 °C over the course of germination. At this point, enzyme formation and activity as well as growth is slow, and respiration is weak. In terms of development, visible signs of growth and indications of modification advance in a parallel fashion. Barley with a tendency to heat up rapidly makes it difficult to carry out cold malting regimes; the temperature rises rapidly in the piece, causing it to dry out. This tendency is dependent on the conditions under which it was cultivated and the characteristics of the barley itself. As a result, barley grown in dry climates and protein-rich barley with small kernels are often more difficult to germinate using a cold regime. In many instances, the barley does not undergo modification at low temperatures, or it is incomplete.

Table 1.7 Heat energy generated during germination.

Germination period	[d]	1	2	3	4	5	6	7	8
Heat energy	[kcal/(t·h)]	320	520	880	1310	1470	1360	1280	1280
	[kJ/(t·h)]	1340	2175	3680	5480	6150	5690	5350	5350

Barley, which is difficult to modify, requires higher temperatures, ranging from 18 to 20 °C, or even up to 22 °C, during the "modification phase" or second half of the germination period. However, the first days of germination must be carried out at cooler temperatures of 12–16 °C in order to prevent uneven growth and variations in enzyme activity. Malting losses are greater at higher germination temperatures. Lighter-colored malt requires a cold germination procedure, but higher germination temperatures are employed to achieve the more extensive modification necessary for producing darker malt.

In recent years, the falling temperature regime has been more favored by operators of modern steeping and germination plants. The grain has a moisture content of 38% or 42% (26 h or 52 h steeping period, respectively) with a temperature of 17–18 °C when it is transferred to the germination vessel. This temperature is maintained for approximately 2 days as the moisture content of the grain is gradually increased. The temperature is lowered to 10–13 °C after the maximum moisture content is reached. The relatively "warm" phase at the start of germination favors rapid growth and the vigorous formation of enzymes. A rapid drop in temperature coupled with a simultaneous increase in the moisture content stimulates more enzyme formation; despite the lower temperatures, modification continues to proceed due to high level of moisture present. This method results in fewer malting losses compared to the conventional malting method.

Modern steeping regimes restrict the uptake of *moisture in the steeping grain* to the level required for the grain to germinate evenly. The required moisture content of 38–40% is not sufficient to achieve the amount of enzyme formation and modification desired. To do so, the moisture content must be raised to 43–48% or even 50%. This occurs through water uptake during the "wet" steeping rest, by spraying the grain or by flush steeping. It is not difficult to maintain the necessary level of moisture in grain germinated in a traditional floor malting space because water lost through evaporation is replaced by that "sweating" or condensing on the surface of the grain. However, there is always a risk of dehydration when using pneumatic germination systems. In these systems, the incoming air is saturated with moisture. Nevertheless, the air is warmed as it passes through the piece, causing a drop in relative moisture. Therefore, the greater the difference is between the air temperature at the inlet and the temperature in the piece, the more moisture will be removed from the grain. The moisture content should be measured daily, since it exerts considerable influence on the metabolic processes occurring in the grain.

The *ratio of oxygen to carbon dioxide* should be as high as possible in favor of oxygen during steeping and the first days of germination, since an adequate amount of endoenzymes can only be formed when enough oxygen is present. CO_2 in the early stage of the growth phase causes a flattening of the life functions in the embryo. In contrast, during the modification phase, a CO_2 concentration of 3–5% can suppress excessive growth. Higher values for CO_2 lead to malt with low enzymatic activity but richer in low molecular weight substances caused by this suppression of growth. In the past, the *germination period* was dictated by the kind of malt being produced and varied widely, depending on the barley variety, the crop year, etc. Since important physiological processes are already occurring in the steeping vessel and the grain starts to germinate after 36–48 h of steeping, the entire steeping and germination period now takes place within 6–8 days. As a rule, this entails 1 day of steeping and 6 days of germination or 2 days of steeping (one of which in a flat-bottomed steep) and 5 days of germination. The moisture level can be increased during this period to obtain more intense modification if desired (for example, as required for dark malt). The steeping and germination period can be shortened by increasing the moisture content in the germinating grain to produce malt with a typical degree of modification. As seen in the following data below, the degree of cytolysis is approximately the same, but the soluble protein is higher, something that is generally not well received by brewers.

This is evident in Table 1.8.

These data allow the following conclusions to be made: a low moisture content in the germinating grain, low germination temperatures, and CO_2 concentrations of more than 5% lengthen the vegetative growth period. In contrast, high moisture levels, higher temperatures, and copious amounts of oxygen serve to shorten it. However, compensating for germination time by increasing the moisture content and raising the temperature will not accomplish all of the desired changes in the individual groups of compounds. Furthermore, it is imperative that barley possesses a high germinative energy, i.e., a high germinative index; otherwise, late-germinating kernels will drastically impact malt quality by lowering the degree of modification and homogeneity. Care must be taken during steeping and germination not to expose the germinating grain to temperature or water shocks.

Table 1.8 The effects of curtailing the steeping/germination period and compensating by increasing the moisture content of the grain.

Steeping and germination	[d]	6	7
Moisture content (grain)	[%]	48	45
Extract difference (EBC)	[%]	1.7	1.7
Viscosity	[mPa·s]	1.53	1.52
Friabilimeter/completely glassy	[%]	84/1.5	87/1.0
Kolbach index	[%]	42.2	39.8
VZ 45 °C	[%]	38.2	37.8

The application of substances capable of promoting or inhibiting growth is also considered to be one of the germination conditions. The effect of exogenous gibberellins can be boosted by abrading the kernel to remove a small portion of the substances found in the hull substances. These types of additives are not permitted in Germany (refer to Section 1.5.3.9).

1.5 Various Malting Systems

1.5.1 Floor Malting

Traditional floor malting is the simplest and most natural method for producing malt. It has largely been replaced with pneumatic malting systems as its capacity limitations and its lower operational reliability and reproducibility (e.g., due to seasonal temperature changes) no longer meet modern standards for quality. With few exceptions, floor malting is now only practiced in smaller facilities, in particular at breweries that also operate their own malthouses.

1.5.1.1 Malting Floors The *space within which traditional floor malting* is carried out should remain at an even temperature of 10–12 °C, regardless of outdoor temperature fluctuations. Malting floors, which readily absorb and retain heat, are less effective if a maltster needs to employ a lower temperature flooring method, i.e., the malting regime. Likewise, the germination process is unnecessarily prolonged on floors that are too cold. This is especially true for barley that is difficult to modify.

Older floor malting facilities were largely carried out underground. Traditional malting floors were only constructed aboveground over multiple levels in locations where the groundwater was high. In such cases, the walls and ceilings require proper insulation. The materials used in the construction of a malting floor are selected for their physical properties: in particular, they should exercise little to no influence on the moisture content or the temperature of the green malt. Clay is deemed the best natural basis for flooring in a facility practicing floor malting. If clay is not available, the floor must be separated from the earthen substructure by layers of various materials. These are applied in the following order, from the bottom to the top: 30 cm of gravel or crushed stone and 30 cm of clay (tamped as the respective layers are laid down); the paved surface is constructed of flat Solnhofen limestone slabs or smooth cement screed. By necessity, the floor is durable and has to possess a smooth, seamless surface. A slight incline allows water to run off into a recessed floor drain designed to prevent any odor from escaping. Gutters are sealed and are mechanically cleaned and disinfected with chlorinated agents (chlorinated slaked lime and chlorine bleach).

1.5.1.2 Artificial Cooling *Artificial cooling* of the floors, where germination takes place, can only be effectively and sustainably achieved through the use of refrigeration systems based on brine, NH_3, or F22. Cooling equipment should be correctly mounted on the ceiling above the floor, so that the malt does not dry out or undergo a disproportionate amount of germination. The germinating kernels can dry out if humidity is removed from the air through condensation on the surfaces of refrigeration lines, whereas overly vigorous germination is brought about by ice melting on the same lines. For this reason, runoff channels made of wood or insulated metal should be positioned beneath the refrigeration lines. Refrigeration systems may also be mounted on the wall in less-spacious rooms for floor malting. However, it is unlikely that a decline in the moisture content can be avoided, making it necessary to spray the piece once or twice during germination. Installation of refrigeration systems extends the period during the year over which malting can be carried out, in addition to significantly increasing capacity. Climate control also ensures that the desired germination conditions are fulfilled. It is less expensive to cool the room than to cool the floor itself. There is no loss of moisture, since the water released by the germinating grain during respiration condenses

on the surface of the floor. The air in the room can be heated in a furnace or with heating elements, but this, of course, also brings with it the risk of drying out the germinating grain. In floor malting facilities, where the piece is germinated under cooler conditions, the depth of the grain is greater in order to maintain a suitable temperature.

1.5.1.3 Moisture Content The *moisture content* of the air is just as important as the temperature in the room where malting is taking place. The moisture content of the air within the entire space should be maintained at a constant humidity of 95% to prevent the piece from drying out. The moisture content is dependent on the volume of air in the room as well as how much air flows in and out. The volume of air within this space is primarily determined by the distance between the ceiling and the floor; therefore, it should not exceed 3–4 m. If the ceiling is too high, it is impossible to maintain the required moisture levels in the air, due to the more vigorous air circulation in the room. This will ultimately cause the grain to dry out. If the ceiling is too low, the air in the room can become musty, and it must be replaced more frequently. If possible, the ceilings in each room containing a malting floor should be of a uniform height. The presence of beams and sharp angles makes it difficult to achieve uniform ventilation.

The air should not be replaced too frequently in the space where floor malting is conducted. Sudden, strong drafts of air should be avoided to prevent the germinating grain from drying out. Ducts integrated into the walls enclosing the space provide ventilation. Air is removed from the highest point in the room and vented to the outdoors. The air channels must be positioned at an adequate height on the wall and must also be able to be sealed. The bottom of the channels should be sloped to prevent any accumulation of water, which may result in possible blockage. Uninhibited currents and gusts of air, such as those that occur in elevator shafts or as a result of unsealed doors or windows, are a design flaw. Likewise, the use of fans to ventilate the space above the germinating malt is generally considered to be a disadvantage. The moisture content of the air can be measured and recorded with psychrometers or hygrometers.

1.5.1.4 The Area Required for the Malting Floor The *area required for the malting floor* is determined by the depth of the grain bed; 100 kg of barley yields 3.2–3.6 hl of green malt. Since the layer of germinating grain is limited to a maximum of 9–10 cm at the peak of the most vigorous growth stage, 100 kg of barley requires an area of 3.2–3.6 m^2. Green malt can be produced from 30–40 kg of barley over an area of 1 m^2 (depending on the temperature of the room).

1.5.1.5 Light Exposure During Floor Malting Exposure to *light* should be avoided during germination. The number of windows should be limited due to the risk of temperature fluctuations. Therefore, artificial lighting is necessary. The *malting floor is usually cleaned* with brushes and brooms. In some instances, the floor is cleaned using a pressure washer to treat it with a simple disinfectant (e.g., slaked lime). If the malting floor is not used for a longer period, then cleaning and disinfection with chlorinated products are recommended. A connection to the water supply should be available in the room where floor malting is conducted.

1.5.1.6 Regulating Germination in the Piece *Regulating germination in the piece*: the proper couching of the grain freshly cast from the steep is essential for *initiating the germination process*. For floor malting, the grain is always cast from the steep "dry." How quickly the moisture on the surface of the grain is taken up and germination commences is dependent on the depth of the wet piece. In couching the piece, the grain can be piled higher (30–40 cm) if steeping has been brief, or if the floor is cold and drafty. In this situation, measures for increasing the moisture content or for preventing the overly rapid evaporation of moisture from the couched grain must be taken. Spreading the grain out in a thinner layer (15–20 cm high) creates a larger surface area, which causes it to dry out more quickly. If the grain has already started to chit when casting the steep, or if the floor where germination occurs is warmer, the depth of the couched grain should be shallower.

The following attributes of germination become apparent once the *couched grain* has taken up its surface moisture: the rootlets begin to become visible (if they had not already done so during steeping). The temperature rises and beads of moisture start to form on the surface of the kernels. From the very outset, it is of utmost importance to ensure that these biological processes do not progress too rapidly. Germination must be properly regulated in order to strike a balance between the enzymatic activity inside of the kernel and the visible indications of growth externally. Germination cannot be adequately regulated if the temperature of the piece rises too rapidly at the onset of germination. Cooling the piece by

increasing its surface area serves as a useful means for preventing rapid and excessive growth during germination. Altering the depth of the germinating piece is one of the ultimate advantages of floor malting. Conducting germination in a piece with a relatively shallow of bed depth allows maltsters to compensate for a broad range of characteristics perhaps unique to a particular crop year or to adapt the process to the type of malt being produced.

The depth of the layer is determined by the temperature of the germinating piece. The dry piece is thinned until the temperature does not exceed 12–13 °C.

Turning the piece is another essential tool for regulating kernel growth and metabolism. Knowing when to turn the piece is a skill that requires the capacity for careful observation, years of practice, and a great deal of meticulous diligence.

Turning effectively mixes and redistributes the germinating grain. It homogenizes the temperature and moisture, while preventing the rootlets from felting, i.e., from becoming interwoven. Furthermore, turning releases the heat accumulating as a result of respiration, allows the moisture on the surface of the kernels to evaporate, and supplies fresh air to the kernels. The effects vary according to how vigorously the piece is turned. The act of turning must be performed at the necessary time and at the correct intervals. If done too frequently, it is not only a matter of additional labor, but it also reduces the moisture content of the piece unnecessarily and stimulates excessive respiration. Cooling the piece by thinning is preferable to more frequent turning. Windows or ventilation ducts can be opened during turning if the temperature outside is not too low. However, they should be closed after the piece has been turned.

A wet piece is turned twice per day. On average, it may be necessary to turn a dry piece as many as three times a day, i.e., every 8 h. The odor rising from the piece is that of freshly peeled cucumbers and should be readily perceptible. The piece should have a uniform depth throughout, unless unusually warm or cool areas are present.

Visible signs of growth appear on the third or fourth day of germination. The rootlets and acrospires become stronger, and the "young piece," as it is known, enters its most vigorous phase of growth. During this time, it is important to ensure that the biological processes do not occur too rapidly or progress too far. For this reason, the piece is thinned out to a depth of 9–10 cm, depending on the temperature and the grain's capacity to undergo modification. The germinating grain occupies the largest volume at this stage. The temperature of the young piece should not exceed 15–16 °C, and the grain is turned once again, depending on how much growth is apparent, usually around 8 h later. The grain reaches the stage known as the "sprouting piece" on the fifth day of germination. Barley readily capable of modification can continue to germinate at the same temperature as the young piece. A warmer regime is used for barley that is difficult to modify or for dark malt. In this case, the temperature is increased by approximately 1 °C per day.

The piece is now turned twice per day. A decline in vigorous growth is often observed in grain steeped for a shorter duration, in grain cultivated and harvested under hot, dry conditions, and in grain germinated quickly on dry malting floors. Moisture scarcely condenses on the surface of the grain anymore after turning, causing the piece to heat up more slowly as well. This signals that the moisture content is insufficient, and that the biological processes in the grain must be artificially stimulated by spraying the piece. Shortly before turning the piece, fine droplets of moisture are applied at a rate of 1–2 l/dt by means of a sprayer attachment or a misting device. The temperature of the liquor should be the same as the temperature of the piece, perhaps somewhat warmer if the floor is quite cold. Liquor is sprayed on the piece after it has begun to germinate. Based on the period over which germination has actually taken place, this would occur on the fourth or fifth day. Spraying the green malt at a later point should only be carried out when producing dark malt, if at all.

On the sixth day, the germinative energy of the piece declines, metabolic processes are weaker, and the temperature ceases to rise as rapidly. If the biological processes have been artificially slowed during the first 4–5 days because the piece was thinned, they must be roused strongly on the sixth day in order to successfully continue germination. This is done by felting, which is essentially allowing the piece to remain undisturbed, floored somewhat deeper, for a period of 24 h or longer without turning. Less movement not only enhances the rate of growth, but the rootlets also become entangled, forming a single mat of interwoven kernels. A considerable amount of moisture collects on the surface of the kernels, and the temperature rises slightly. Felting enhances the modification of the barley kernels. Thus, it is especially employed in the production of highly modified malts or for barley less inclined to undergo modification. In these instances, felting may even be employed twice: from day 5 to day 6, the piece is allowed to commence felting for 16–18 h, followed by 24 h

of no movement whatsoever. This technique is either briefly employed with barley that undergoes modification more readily or not at all. Respiration is slowed through the accumulation of CO_2 in the green malt. Growth wanes somewhat, and as a result, the amounts of low molecular weight substances (sugars and amino acids) increase in the kernels. The temperature of the felting piece reaches 18–22 °C. When it is time to turn the grain, the piece is matted together and must first be "cleared"; i.e., the felted kernels have to be separated from one another by lifting them with a pitchfork and disentangling them. On the eighth (and following) day, the malt is referred to as the "old piece," denoting that it is in the final stage of germination. There is less condensate collected on the surface of the kernels, with growth lessening as time goes on; turning is seldom necessary. By this time, the desired level of modification has been reached. Traditionally, germination lasted between 7 and 8 days for lighter malts and between 8 and 11 days for dark malts. Today, germination is achieved in a mere 5–6 days, with the barley varieties currently available to maltsters, which are more conducive to modification, and given the modern techniques for increasing moisture levels in the grain during the process. This is particularly true if the kernels are already chitting uniformly when the grains are cast out of the steeping vessel.

Assuming that the temperature of the floor is low enough, grain can be successfully germinated under a range of conditions in a floor malting facility. The temperature of the piece can be regulated by assiduously adjusting the surface area as needed. Depending on the degree of modification, the surface area can be increased or decreased, although this is subject to the area of the malting floor. In the germinating grain, it is relatively simple to maintain the moisture level achieved during steeping of 45%. This phenomenon is quite surprising since the expectation is that a loss in moisture would be inevitable, given that the piece is thinned out and turned several times per day. However, the moisture in the piece that is lost is also replaced by the moisture generated through respiration. Water vapor or "sweat" formed during respiration condenses on the surface of the kernels. It is immediately absorbed by the fine rootlets on the barley kernels. This is the only reason that the moisture content in the piece remains constant despite it being turned and thinned. The formation of "sweat" on the surface of the kernels is also a practical and reliable measure for gauging the level of respiration and metabolism occurring in the grain. While it is relatively easy to maintain the moisture in the piece, it is nevertheless difficult to increase the level of moisture in the germinating kernels by more than 2–3% (absolute). Spraying results in increased growth and more respiration, making it difficult to maintain the proper temperature in the piece. This phenomenon only plays a lesser role in the production of dark malts, particularly toward the end of germination.

The carbon dioxide formed during respiration flows out of the piece. A maximum of 1–2% carbon dioxide remains in the piece, since the germinating grain is spread out in a very thin layer. The concentration of carbon dioxide is somewhat higher during the first few days of germination and when the piece is left undisturbed (the felting piece). For this reason, the amount of gas exchange is sufficient; thus, no special supply of air is necessary.

1.5.1.7 The Capacity of Floor Malting Operations The *capacity of a floor malting operation* depends on the area of the malting floor, the space required for germinating the green malt, and the duration of the entire malting process, particularly that of the germination period. Given a 7-day germination period and assuming 240 days per year for malting operations, the malting floor can be utilized approximately 34 times. If 0.35 dt of barley occupies a space of 1 m^2 on the floor, the combined area of seven malting floors, each with a total surface of 250 m^2, would equal 1750 m^2. With each piece amounting to 87.5 t, seven pieces would add up to a malting capacity of 612.5 dt of barley. Utilization of this total area for 34 malting cycles results in a capacity of 20,825 dt. Thermometers are inserted into the piece at different locations to a depth of 2 cm above the floor to monitor the temperature during germination. Preferentially, the temperature data would be depicted as a graph rather than simply being recorded in list form.

Floor malting is the most natural method for producing malt but is also accompanied by its share of economic disadvantages. Since this method is dependent on the ambient temperature outdoors and ultimately on climate conditions, full utilization of the possibilities offered by floor malting is limited, and the results exhibit significant variation. This deficiency can only be partially compensated by refrigeration. The space required is extraordinarily high, amounting to approximately 3.2 m^2 for each 100 kg of barley. The construction and maintenance of the buildings requires significant capital investment. The ongoing costs of operations are high. A large number of trained employees are needed to move and turn the piece from 12 to 16

times over the entire germination period. The work required from a maltster is dependent on the stage of germination. It varies from turning the wet piece (50 dt/h) to the young piece (35 dt/h) to felting piece (25 dt/h, including shaking to disentangle the kernels). On average, a maltster can process approximately 35 dt/h; the daily output is around 200 dt per person, which also involves performing other work-related tasks.

1.5.1.8 Floor Malting Designs *Various floor malting designs*: the large amount of space and manual labor required to carry out floor malting has led to the design and development of alternative malting methods over the years. One method entails simplifying the process and reducing the amount of necessary manual labor. This can be achieved by employing a plow to replace turning by hand, which has the added benefit of positively impacting the malting process. The piece is only turned manually one time per day, while a plow is used for the second. Plowing redistributes the barley in the piece, loosening and lightly aerating it; however, it does not accomplish the same effect of moving it in layers as is the case with manual turning. The barley remains enveloped in a carbon dioxide gas atmosphere, and respiration is suppressed, resulting in fewer losses during malting. The plows feature shovel-like blades, typical of those on agricultural equipment. Simple mechanical plows featuring motor-powered propellers are also utilized to effectively turn the grain. In many instances, the grain does not need to be turned by hand if the appropriate plowing techniques are employed. Pitchforks as well as various other traditional hand tools (known in German as *Prismenschieber* and *Fensterschieber*) were utilized to disentangle the felted piece early in the germination process and to work the piece over the entire expanse of the malting floor. There are also turning machines that imitate how the grain is thrown with a shovel. These freely mobile turners on wheels have proven to be very effective with grain in the young, felting, and old piece stages of germination. These turners can be used in any floor malting facility. In addition, there are also turners available that move on rails. Their design requires all of the malting floors to be constructed in the same shape and dimensions. The former design is usually found in smaller or older floor malting operations, while the latter is limited to larger, specially constructed floor maltings. It is precisely this design that allows the mechanization of processes, such as casting the grain out of the steep and clearing the floor of the piece, so that it can be transferred to the kiln. From a technical standpoint, it has proven to be practical and moreover saves a great deal of manual labor. The system is capable of producing approximately 900 dt of malt per employee. Nevertheless, despite the advancements brought by these mechanical germination systems, they cannot overcome the two remaining disadvantages inherent to floor malting: the dependency on ambient atmospheric conditions and the large space requirement. In the end, a solution was found to meet these challenges through an entirely different system, namely pneumatic malting.

1.5.2 Pneumatic Malting Systems

A characteristic feature of all pneumatic malting systems is that the grain is processed in a deep layer. This is only feasible if the germinating grain is cooled with conditioned air, meaning that the air is saturated with moisture. Cooling the piece to a sufficient degree – without removing any moisture – is one of the most important but also one of the most difficult tasks in pneumatic malting. A deep layer of germinating grain undergoing intensive growth requires a large supply of air.

Another important task of the air flowing through the grain is to maintain the desired level of moisture in the piece. This is not easy to accomplish, since the air heats up as it passes through the piece, potentially extracting moisture from the grain. For this reason, moisture is not allowed to condense on the grain. Finally, air flowing through the piece should remove carbon dioxide gas and introduce fresh air, which is attainable with just small volumes of air.

Each pneumatic germination system consists of ventilation equipment in addition to the actual germination vessel.

1.5.2.1 Ventilation Systems The *ventilation systems* are the same in all pneumatic systems. Their design and dimensions are critical for proper function of the system. They consist of:

1. elements that condition the air before it passes through the germinating vessel (attemperation and humidification)
2. a duct system (for introducing fresh air, recirculating air, and exhaust air) and
3. fans, which move the air through the germination grain in the vessel.

1.5.2.2 Dedicated Purification Systems A *dedicated purification system* for the outside air is only rarely encountered. The system is used to filter out the dust from the fresh air. This avoids

contamination with microorganisms and the accumulation of biofilm deposits in the ventilation system. The air is either filtered, or it may be scrubbed in special chambers using finely atomized water droplets.

1.5.2.3 Devices Used for Attemperation The *devices used for attemperation* bring the ambient temperature of the outside air to that required for germination, approximately 10–16 °C. The air entering the piece must always be cooler than that of the piece. However, excessively low temperatures should be avoided; otherwise, the germinating grain may experience a temperature shock, or too much moisture may be lost. Therefore, the air from the outdoors must be warmed in the winter and likewise cooled during the summer months.

The incoming air can be heated as it is conditioning by heating the water supplied to the spray nozzles. Directly blowing in steam, which must be purified, also accomplishes the simultaneous conditioning of the air. Steam-heated radiators dry the incoming air. However, the incoming air must be warmed even more than usual (e.g., to 15–16 °C), since the subsequent saturation of the air with fine water droplets lowers the temperature. Another heating option is to utilize return air. The air exiting the piece is captured and reused. The return air may be blended with fresh air, depending on the target temperature. This method has proven to be very successful in controlling the temperature in large malting systems.

The temperature of the air can be lowered by spraying it with fine droplets of cold water or with a dedicated refrigeration system filled with brine, cold water at 0.5 °C, or direct-evaporation refrigerants such as ammonia and Frigen.

From a physical standpoint, there are two options for cooling the air with water:

(a) Cooling brought about by the evaporation of water: this only occurs if the air to be cooled is not already saturated with water vapor.
(b) Cooling by contact, i.e., transferring the water temperature to the air through direct contact: the finer the water droplets, the more effective the transfer is, and the longer the contact time is between the water and the air. If the ambient temperature outside is too high, then it will not be sufficient to cool the water. Pre-chilling the water can improve the cooling effect; however, it is most common today to cool the air directly in a refrigeration system. Brine is no longer commonly used as a refrigerant. However, glycol or ice water at 0.5–1 °C is once again gaining in importance due to the concerns regarding refrigerants that function on the basis of direct evaporation. Peaks in electricity consumption can be avoided by storing the "cold" in reservoirs in the form of various media, most frequently as ice water. Nowadays, ammonia is preferred to Frigen (F22 instead of F12) because leaks in the system can be easily detected. The temperature of the direct-evaporation refrigerant is set high enough (at 0 °C), so that ice deposits do not form on the cooler. The refrigeration system must be adequately dimensioned, so that it can cover the "heat spikes" generated by respiration during germination. This will determine the temperature of the fresh air required and the subsequent management of the germination process. Traditional malting methods require a cooling capacity of approximately 6270 kJ/(t·h) (1500 kcal/(t·h). Modern methods, such as those supplying moisture over several additions and applying a falling temperature regime during germination (refer to Section 1.5.3.3), lead to a higher peak due to the shorter processing periods. In this instance, an increase in cooling capacity of up to 50% is warranted. The compressor should have a capacity of 9600 kJ/(t·h) (2300 kcal/(t·h) for areas on a comparable latitude to western Europe. Some germination systems may require an even greater output.

The refrigeration system may be positioned up- or downstream from the fan. It allows automated control of the germination process.

1.5.2.4 Artificial Humidification *Artificial humidification* of the air is an absolute necessity, not only because the piece is always at risk of drying out but also for the following reasons:

1. Each strong draft of air causes moisture to evaporate, effectively removing water from the piece.
2. The germinating grain is cooled by passing air through it. As it flows through the piece, the air absorbs heat, thus increasing its capacity to carry more water. The greater the temperature difference between the incoming air and the germinating grain, the more water is removed.
3. The flow of air prevents the grain from "sweating," i.e., condensation forming on the surface of the kernels. The water vapor produced as a result of respiration is immediately carried away with the air.

The incoming air must be saturated with the finest water droplets possible to compensate for these inevitable losses in moisture. Artificial humidification can be achieved with spray nozzles. In older germination systems, misting with water simultaneously cools the air. The misting systems are housed in dedicated conditioning towers where they carry out the functions described above. In systems equipped with dedicated cooling devices, the spray nozzles are located in the duct from which the incoming air flows into the germination vessel. Rotary atomizers may also be employed to humidify the air. Care must be taken to ensure that no water droplets pass through the germination deck to the germinating grain if the air only travels a short distance after it is saturated by spray nozzles or rotary atomizers. At this stage of the process, there is the danger that the rootlets will grow through the slits in the deck and block the passage of air, causing a partial warming of the piece to occur. *Conditioning towers* are utilized to humidify the air and are positioned in close proximity to the germination system. They usually consist of two parts to extend the contact between the air and the water droplets for the longest period possible. The towers must be easily accessible, so that the spray nozzles can be cleaned. A ladder for climbing up into the tower is mounted on the wall.

The air is humidified in the conditioning towers using spray nozzles. Water usually flows through a narrow opening in the nozzle and hits a deflector plate, creating tiny water droplets. The resulting mist is taken up by the air as it passes through the tower. Generating a fine mist of water requires the proper construction and adjustment of the nozzles, sufficient water pressure, and maintaining the cleanliness of the nozzles and supply lines.

A water pressure of 2–3 bar (overpressure) is common. A special pump may be installed if the existing water pressure is too low. The nozzles should be distributed in the humidification tower to achieve the best utilization of the misting zone. The number of nozzles is determined by the rate of airflow and the spray area. Each nozzle sprays approximately 1–1.5 l/min of water under normal pressure conditions.

To reduce water consumption, the excess water is collected from the bottom of the tower and stored in pits below ground. After sedimentation of any particulates present, the water is disinfected by adding chlorine and then pumped back to the spray nozzles for reuse. It is important to keep these water pits clean, otherwise a biofilm slime layer will form on the humidification equipment.

A *rotary atomizer* is another option for humidifying the air. The humidifier is constructed as a drum which contains a fan, a mist-generation device, and a motor enclosed in watertight housing. The motor is positioned directly at the air inlet of the respective germination vessel. A turbo atomizer can be employed to generate an extremely fine spray to achieve a saturation level of 100% moisture in the air. The air is cooled through the loss of heat as a result of evaporation. Although this saturation level can be attained with very low volumes of water, the high proportion of moisture in the warm air prevents it from being cooled to the extent desired. This is due to the fact that the large volume of water required for contact cooling in the conditioning tower is not present. Therefore, a turbo atomizer can only be utilized during the warmer seasons of the year when paired with a refrigeration unit.

The air drawn out of the germination vessel possesses a high degree of saturation. If this air is cooled by a refrigeration system (return air cooler), its complete saturation may even cause a net loss of moisture to occur. Thus, reusing the return air is considered to be a very effective measure in achieving a uniformly high level of moisture in the incoming air. However, this still does not eliminate the need for a turbo atomizer or several rows of spray nozzles for subsequent adjustment, since moisture is often lost as the air flows through the ducts, making it necessary to adjust the level through spraying.

This sort of moisture loss in the piece can be rectified by either spraying more or by elevating the target moisture of the germinating grain (e.g., to 50% instead of 47%). However, this may promote excessive acrospire growth, bringing about the corresponding malting losses.

Water consumption during the entire germination period (158 h under moist conditions) can vary greatly, depending on the given situation. If contact cooling or evaporative cooling is used exclusively in the humidification tower, the process requires water volumes of approximately 30 m^3/t. With a water recovery system, the volume of fresh water amounts to 2.5–5 m^3/t. Turbo atomizers require 0.5 m^3. Water volumes of 0.1–0.5 m^3 are sufficient to cool air using refrigeration systems or for air needing only a slight adjustment in moisture. However, the condenser of the refrigeration unit also requires adequate amounts of water to cool it. This can be as much as 30 m^3/t for a counterflow condenser, 3 m^3/t for an evaporative condenser, or no water at all in the case of air condensers. An air condenser positioned at the fresh air inlet of the

kiln in combination with a tube-in-tube condenser can be employed to recover the heat and use it to warm the steep liquor.

1.5.2.5 Duct Systems The *duct system*, i.e., the path along which the air is routed, must be designed so that the temperature as well as the moisture content of the air remain unchanged. Fresh air should always be introduced from outside of the building and not from the floor malting room. The duct that carries the fresh air should be adequately dimensioned. The return air duct directs the air exiting the germination vessel to the fan. It can be separated for each unit or arranged so that several germination units can be vented simultaneously. Precisely, this type of return air duct, one that collects air from several units, acts as a holding area for warm, moist air that is low in oxygen. This air can be used to enhance germination conditions. Spray systems with nozzles or those with their own refrigeration devices are employed to lower the temperature of the return air. The exhaust air duct should be dimensioned, so that the air can be vented without any resistance.

All air ducts should be as short and straight as possible; they should have a correspondingly large, consistent diameter but with the smallest surface area possible. The interior of the ducts should be smooth and easy to clean.

Sealing devices must be installed, so that they do not cause a narrowing of the diameter of the duct which would change the moisture content of the air. On the other hand, they should be able to completely close off the duct if necessary.

1.5.2.6 Fans *Fans*: the movement of air is brought about by the generation of pressure differences. Fans that exert pressure and suction are employed for this purpose. These fans are either surrounded by a housing, or they are radial or axial in design. Pressure fans are considered to be preferable from a technical standpoint, since the pressure causes the air to be distributed evenly throughout the germinating grain. As a result, the same overpressure is found at every point beneath the piece. In contrast, the airflow created by suction fans may aerate some areas of the green malt more strongly than others due to shorter distances or less resistance.

Fan performance can be assessed by measuring the difference in pressure between the upper and lower layers of the piece. The measurement also provides insight into the nature of the germination unit, the position of the gate valves regulating the airflow, and the permeability of the grain bed, e.g., before and after turning.

The volumes of air used to cool and ventilate the piece should be adjusted relative to the individual stage of growth. For this reason, the capability to regulate the speed of the fan motor in a stepless manner, e.g., through a variable frequency converter, is more economical than throttling the volume of fresh air or exhaust air. Excessive air speeds disrupt the moisture conditions in the germination box. Particular emphasis is placed on achieving uniform ventilation throughout the grain bed. Ventilation can be constant or supplied at intervals. Constant ventilation is preferable, since it helps to maintain uniform temperature patterns, thus preventing interference with growth. In this case, the airflow generated by the fan ranges from 300 to 700 $m^3/(t \cdot h)$, depending on the stage of germination. If ventilation is only carried out intermittently, then a higher rate of airflow is required, since the piece must be cooled within a short period of time. Fans with an output in the range of 1000–1500 $m^3/(t \cdot h)$ should be installed.

1.5.2.7 Automatic Temperature Control *Automatic temperature control*: the temperature in the piece can easily be regulated automatically with a thermostat if it is cooled artificially, e.g., through refrigeration. The temperature of the incoming air is measured under the deck in the germination unit. The evaporator on the refrigeration system influences the temperature of the incoming air at a set ratio of fresh air to return air. The difference between the temperature of the piece and the incoming air depends on the volume of air being moved. It is possible to control the fan speed by setting a difference in temperature, e.g., 2 °C. If the temperature in the grain bed (usually measured in the uppermost third) exceeds the preset value, then fan switches to the next higher speed or, conversely, to a lower speed if the opposite occurs. During the colder seasons, the ratio of fresh air to return air is selected, so that the refrigeration system can regulate the temperature with the minimum amount of cooling through full automation.

However, in order to also save this electricity, the flaps for the fresh air and the return air on each germination box can be controlled by means of a thermostat to constantly maintain the desired temperature (measured beneath the deck). The composition of the incoming air is not taken into account. The refrigeration system is set to automatically cycle on if the temperature cannot be maintained within the preset range.

1.5.2.8 Powering Pneumatic Malting Systems *Power requirements for pneumatic malting systems*:

it varies greatly due to the numerous ventilation and refrigeration options, the different bed depths (high specific bulk loading densities – higher pressures – more power needed), and the dimensions of the ductwork.

The power required for ventilating germination boxes can be calculated based on the following metrics:

The fan output is 500 $m^3/(t \cdot h)$ for a germination period of 144 h with 136 h of ventilation. During this time, the fan operates for 100 h at a lower speed and 36 h at a higher speed with a motor efficiency of $\gamma = 0.85$. A germination box containing 80 t of barley as green malt results in power requirements of 2.2–9 kWh. On average, approximately 5.8 kWh/t of barley or 7.2 kWh/t of malt is required.

Power consumption of the refrigeration system yields the following data:

The average running time is 18 h on a total of 330 workdays/year. The efficiency is 80%, with an average consumption of 35 kWh/t for barley or 44 kWh/t for malt. Power consumption can be reduced by implementing the measures described previously. Ice water can also be used in cooling systems instead of a direct-evaporation refrigerant. The "ice buildup" allows the use of less-expensive, off-peak electricity for cooling operations.

Higher condenser temperatures (e.g., operation as an air condenser in the summertime) can lead to increased power consumption. A tube-in-tube condenser installed downstream can lower the condensation temperature while concurrently heating water to be used in the steeping process.

1.5.3 Germination Vessels in Pneumatic Malting Systems

Pneumatic malting systems are categorized according to their various designs; nevertheless, they are all derived from two primary types of systems: drum and box malting.

1.5.3.1 Drum Malting Systems A number of different variations on *drum malting systems* were available earlier, but now only two exist, the Galland drum and the box germination drum.

The *Galland drum* consists of a wrought iron cylinder, closed on both ends and resting on four rollers. Circular openings cut in the floors allow air to be forced into and out of the drum. Air entering the drum on the inlet side is not routed directly to the interior of the drum but rather to a separate antechamber. Perforated ducts connected to this antechamber run along the wall of the drum around the perimeter. The air flows into these ducts and toward the interior of the drum into the germinating piece. A broad, perforated shaft is mounted in the center of the drum on its axis in order to vent the carbon dioxide-laden air released by the germinating grain. This central shaft is connected to the air-discharge system. As the drum rotates, all of the air inlets on the central shaft situated above the surface of the grain are blocked by a pendulum gate valve to prevent the air entering the drum from escaping unused. One to two rows of small, sealable hatches are evenly distributed around the circumference of the drum. These openings allow the drum to be loaded and emptied and also provide access to observe the grain during germination.

The germinating piece is turned by the slow rotation of the drum with assistance from a worm drive that turns on a worm wheel mounted around the circumference of the drum. It takes 25–45 min for the drum to make one rotation. The lower speed is used to turn the germinating piece, while the higher one is intended for loading and emptying the drum. The surface of the grain is inclined, causing it to slowly spill over itself as the drum rotates. As a result, the grain is turned thoroughly and very evenly. At one time, Galland drums had a maximum capacity of 15 t, while newer designs can handle up to 25 t of grain.

Galland drums are ventilated continuously. Because these drums are usually many years old, they were installed with a centralized ventilation system and the suction fans commonly encountered at that time. Centralized ventilation has the inherent disadvantage that the temperature of the air it supplies is determined by the coldest piece; for example, if the temperature is 12 °C in a piece, then the temperature of the incoming air must be 10 °C. At this low temperature, relatively small volumes of air are required for the green malt at an advanced stage of germination. However, the green malt loses large amounts of moisture due to the drop in relative humidity that occurs as the air is warmed from 10 to 15 °C or even to 18 °C. This poses a risk of drying out the piece, which must be avoided by the targeted application of steep liquor through spraying. In addition, ventilation using suction fans has its own concomitant disadvantages. The vacuum exerted at the air-on side is around 5 mmAq and approximately 40 mmAq on the air-off side. The ventilation effect is not quite uniform, since the depth of the germinating grain varies due to the circular cross section of the drum and its rotation. Moreover, aeration and carbon dioxide removal are less pronounced on the inlet side of the piece than on the exhaust side because

the fan is mounted on the exhaust side. The piece is thus always colder and drier on the exhaust side as well. The central shaft where the carbon dioxide-laden air is removed from the piece has fewer perforations on the exhaust side than on the intake side to compensate for this effect.

The incoming air is moistened and attemperated in a central conditioning system. From there, it flows through a primary air duct in the masonry, which should be as short and straight as possible. Branches lead off from the primary duct to supply air to individual malting drums. These changes in the direction of the airflow also result in a loss of moisture.

Ventilation is implemented in a modern or converted drum malting system using compressed air. Each drum is individually conditioned and cooled, simplifying the design and construction. However, a duct to handle recirculated air must be integrated into the base of the drum or in another suitable location, since this is ordinarily absent in the aforementioned centralized ventilation system. Fresh and recirculated air are blended in a bifurcated duct prior to reaching the blower, which is downstream from the evaporator of the refrigeration system. Several spray nozzles are sufficient to moisten the air over the short distance to the drum. The volume of air is measured by regulating the fan speed as well as by throttling the exhaust air gate valve.

Malting in the Galland drum creates conditions during germination identical to those found during floor malting or in other pneumatic systems. Certain differences can arise, however, due to the individual characteristics of the various drum designs. The following aspects are important for malting in drums:

These include the temperatures of the air entering and exiting the drum, the time required for rotation of the drum, and the turning of the grain as well as the period during which the drum is stationary. The temperature of the air flowing into the centralized ventilation system is around 10 °C and is therefore the same for all of the drums. The air should encounter very little resistance moving into the interior of the drum (thus, no throttle valves are present). The volume of air is regulated solely by means of a shut-off valve on the exhaust side of the drum.

The time required for rotation of the drum and the turning of the grain is adjusted for each individual stage of germination. The conditions with regard to ventilation are not quite optimal and can result in slight disparities in the temperatures at a range of depths in the grain bed. This makes it necessary to frequently turn the grain, especially at the stages of most intense growth.

Malting in a drum with a centralized ventilation system is generally carried out as follows:

The steep is cast out, either wet or (preferably) dry, through the small hatches mentioned previously. The process of casting out is executed, so that the grain exits the drum in three portions. Therefore, each portion is evenly distributed by one and a half to two rotations of the drum. Historically, prior to casting out, the piece in the drum was steeped to a moisture content of 46–47% in order to counter any ensuing loss of moisture. At that time, it was customary to allow the drum to rotate with maximum exposure to air. The drum was ventilated with unconditioned ambient air until the surface moisture on the grain had evaporated, about 4 h (in summer) and 6–8 h (in winter). Subsequently, the drum was supplied with conditioned air.

More recently, commencing the process with a lower moisture content of 38–42% (after 26 h or 52 h of "pneumatic" steeping) has been adopted. Ventilation begins in earnest only after the grain has absorbed its surface moisture. Carbon dioxide is drawn off at intervals (once every hour for 10 min) until the surface moisture has disappeared. The drum either rotates continuously (at 38% moisture) or for a period of 2 h every 3 h (at 42% moisture). As soon as the temperature of the piece exceeds that of the grain when it was cast out of the steep by approximately 2 °C, the drum is furnished with conditioned air in order to regulate the temperature of the piece.

This method is more natural in practice than the one previously described since no evaporative cooling takes place and therefore no drop in the temperature of the germinating piece.

Earlier malting regimes called for the drum to be rotated for 1 h on the first day of germination, followed by a rest of 4–6 h with an exhaust air temperature of close to 12 °C. The pneumatic gate valve is only opened slightly. The long rest and the resultant warming of the grain serve to encourage uniform germination if it has not already begun with proper steeping.

The drum must be rotated frequently on the second day of germination in order to ensure that the conditions during germination are uniform throughout the piece. After the drum rotates for 1 h, it remains stationary for a period of 3 h. Through adjusting the pneumatic gate valve, the temperature of the exhaust air can be maintained at 12–13 °C.

The drum is rotated for approximately 2 h on the third day of germination and is then held stationary

for 3 h. Depending on the conditions in the drum, the temperature of the exhaust air is 13–14 °C. It may be necessary to rotate the drum for 1 h after a stationary rest of 2 h during warmer seasons. During the stage of strongest growth, heat is generated more intensely in the germinating grain. For this reason, the temperature varies throughout the piece. In order to maintain a uniform temperature, the germinating grain should not be allowed to rest for longer periods without being turned. Excessive warming of the piece can cause felting, when the rootlets intertwine to form a mat. At the very least, this can be inopportune, but it may also endanger the germinating grain. The warmer the temperature outdoors, the shorter the rests must be. It is during this stage of development that the significant temperature difference between the outgoing and incoming air begins to have an impact on the moisture level of the germinating grain. Therefore, it is advisable to first spray the piece after approximately 60 h of germination. This can be accomplished quite simply during one rotation of the drum with a hose connected to a spray nozzle. The excess liquor runs out through the small hatches positioned in a row around the drum. Frequently, a larger volume of liquor is sprayed on the exhaust air side. If the grain is steeped only briefly, factors, such as higher outdoor air temperatures, can necessitate spraying the piece twice (after 48 and 60 h) for optimum growth to occur.

The drum is rotated for 1–2 h with a stationary rest of 2–3 h on the fourth day of germination. The temperature of the exhaust air is 15–16 °C. This facilitates uniform growth of the rootlets. In order to keep the rootlets sufficiently hydrated, the contents of a typical Galland drum must be sprayed intensely twice a day, preferably as turning commences.

Metabolic activity has already peaked by the fifth day; the duration of the rests is gradually extended to stimulate growth in the rootlets. To foster this development, the drum rotates for 2 h and then remains stationary for 4 h. Depending on the degree of modification, the temperature of the exhaust air is 16–18 °C. On the fifth day, the piece is also sprayed twice. The detrimental aspects customary when the germinating grain has been sprayed with large volumes of liquor are eliminated, even at this late stage, by intense mixing of the grain with liquor.

On the sixth day of germination, the drum alternates between rotating for 2 h and remaining stationary for 5–6 h. The temperature of the exhaust air is 18–20 °C and is dependent on the barley. The grain might need to be sprayed again if there is a significant temperature difference between the exhaust air and the incoming air. A sizeable temperature difference can result in a loss of moisture in the germinating grain. The decision to supplement the moisture in the piece with additional liquor is made based on the degree of modification and moisture content of the grain.

On the seventh day of germination, the piece is turned for 2 h every 10–12 h. The temperature of the exhaust air is approximately 18–20 °C. This amount of time is generally sufficient for germination, that is if the proper malting techniques are employed. As a measure to reduce the weight on the deck of the kiln, some maltsters allow the drum to rotate for 6–12 h while it is being ventilated with unconditioned ambient air shortly before the green malt is cast out into the kiln.

This practice outlined above varies, depending on the crop year and the grain's susceptibility for undergoing modification, but it is also subject to the conditions specific to the germination system.

The more intense work of turning the grain must begin earlier if, for example, the grain is already germinating evenly in the steeping tank, which is the case in pneumatic steeps (at a moisture content of around 42% when cast out). This usually is started 1 day earlier. The grain is sprayed to achieve the maximum moisture content; therefore, the first addition of liquor occurs approximately 24 h after the steeped grain is cast out, when all of the kernels are uniformly forking. A second round of vigorous spraying is then required about 12 h later to raise the moisture content to 46–48%. All subsequent steps must focus on maintaining this level of moisture.

The drum is emptied by opening the sliding hatches to allow the green malt to fall into a funnel-shaped chute, which feeds a vibrating conveyor, a belt conveyor, or Redler chain conveyor. Less commonly, the chute feeds a suction port, used to cast out in a pneumatic system.

If the green malt in the drum has been processed properly, it should exhibit a fresh odor, and as a result of gentle handling, the majority of the rootlets should be intact. Acrospire and rootlet growth as well as the degree of modification should be continually monitored throughout the entire germination process. Development of the rootlets is enhanced through long rest periods. By contrast, acrospire growth is promoted by more frequent or longer turning sequences in conjunction with spraying. Modification is favored by longer stationary periods starting on the sixth day

of germination, usually coupled with a somewhat warmer temperature in the drum.

Ordinarily, germination in a drum more strictly follows a set malting regime than is typically the case with floor malting. This kind of malting does indeed benefit greatly from the drum always having the same dimensions as well as superior control over the conditions during germination. Regulating the temperature in the piece can be adapted to any requirement, provided that the respective cooling systems possess the capacity to consistently cool the incoming air to the necessary temperatures during warmer seasons. Germination according to a falling temperature regimen would even be feasible if each drum were equipped with a blower fan and an air cooler. When a centralized ventilation system and suction fans are employed, it is extremely difficult to maintain the moisture content in the germinating grain due to the significant differences in temperature between the malt and fresh air. The complicated path of the airflow also plays a role. In spite of this, thorough turning of the piece makes it possible to continue to spray the green malt up to a late stage in germination, enabling the moisture content to be successfully raised with no disadvantages for the grain. Furthermore, a resteeping of sorts can be carried out in the drum. Depending on the structural aspects, after 60–70 h of germination, the drum can be filled from ¼ to ⅖ with steep liquor. As the drum rotates, the water evenly covers the grain, essentially converting the drum into a temporary steeping vessel.

The piece contains a slight amount of carbon dioxide (approximately 1%). The concentration can reach as high as 7% in the lower portion of the piece only if the grain is allowed to stand for a longer period. Recirculating the air in a completely sealed system through an individual drum (or in one ventilated with a blower) can cause the carbon dioxide content in the piece to rise to 10–15%.

Cleaning and maintenance are prerequisites for proper function of the system. The central air shaft and the peripheral ducts must be cleaned immediately after the drum has been emptied to ensure that the slits remain open. Otherwise, blockage of the slits will lead to temperature variations in the piece. Consequently, in such a case, it would be virtually impossible to prevent the piece from warming up. The manway doors on the central shaft must be closed and secured. If they were open while the drum is in operation, the germinating grain would fall into the central shaft, and uniform ventilation would become unachievable. The ducts conveying the incoming fresh and exhaust air must also be cleaned. The exhaust air duct, in particular, is contaminated with husks and rootlets, which have been blown into the shaft.

When cleaning the external wall of the drum, water must not be allowed to enter the oil reservoirs for the worm drive. The mechanical portion of the drum germination system requires regular maintenance.

Compared with floor malting, the drum system is economically superior in terms of space savings and independence from climate conditions. Furthermore, fewer employees are required for conducting operations, and the process can be monitored and controlled more easily. Individual drum ventilation combined with refrigeration enables automatic temperature adjustments to be made to the germinating grain. Water and power consumption are determined by the design of each system.

1.5.3.2 Germination Drum Systems The *germination drum system* is a combination of a drum and a Saladin box (refer to Section 1.5.3.3). The germinating grain lies on a horizontal support plate located inside the drum.

A newer design uses steel strips, approximately 12–15 cm wide, which are welded in a spiral to the internal wall of the drum. As the grain is cast out of the steep, the drum rotates at a rate of one revolution every 6½ min. These strips serve to distribute the grain evenly and to level it in the drum. When germination is complete, these strips assist in moving the green malt to the small hatches located at the center of the drum mantle. To turn the piece, the speed of the drum is slowed to a single revolution every 13–20 min.

Germination drums are usually ventilated with a blower, so that the air first flows into a separate pressure chamber on the front of the support plate, similar to a Galland drum. Air is pushed through the germinating grain and exits through a second air chamber positioned on the opposite side of the drum floor. Each germination box drum is equipped with its own fan and humidification device. Modern systems are also equipped with a refrigeration system for direct evaporation of the refrigerant. The turning process is similar to that in the Galland drum. However, due to relatively minor temperature differences in the piece, the grain must only be turned twice a day. This increases to 3–4 times per day during the period of the most intense growth. Turning takes 1 h (about three rotations). The ventilation system must be switched off during this time. This is accompanied by a temperature increase, which is unavoidable and must be compensated for either before or

after turning. After it is turned, the grain settles at its natural angle of repose and therefore must be leveled by moving the drum back and forth until it is horizontal.

After this adjustment, the grain lies flat, and the bed depth is the same throughout. The ventilation in this type of system is more uniform than in a drum. The ducts are short and uncomplicated with a larger cross section. For this reason, as well as to save on capital investment costs, the germination box drum is also designed as a dual-piece system.

The conditions described above allow for more moisture to be retained in the green malt. The moisture can readily be increased through spraying as in the drum. Because the system can be completely sealed, a carbon dioxide rest can be applied. The air can also be continuously recirculated through the system in order to enrich the air in germinating grain with CO_2 in a targeted manner. The germination box drum is subject to continuous ventilation except during periods of rotation, when the piece is being turned. Large quantities of CO_2 evolve when the grain is being turned, but they are quickly dissipated once the ventilation system is switched on. The overpressure under the deck ranges from 50–60 mmAq for a standard bed depth of 1 m. It is approximately 20 mmAq above the surface of the bed. The germination box drum allows for a variety of germination conditions, while turning accomplishes a thorough mixing of the piece. Germination box drums offer several advantages absent in drum systems and in germination boxes. However, they have yet to find widespread acceptance due to their limited capacity of 25 t. It is much easier to clean and maintain the mechanical parts of this kind of system compared to a Galland drum.

1.5.3.3 Box Malting *Box malting* has become widespread throughout the industry, especially in the past 45 years. Of the pneumatic malting techniques available, box malting is practiced almost exclusively. These malting systems are often named Saladin boxes after their inventor. Further developments such as tower malting plants and the different variations on the *Wanderhaufen* transposal system are based on the principle of box malting.

Unlike a germination drum, a germination box is not enclosed; it is open on top and rectangular in shape. The germinating grain is spread out to form a flat layer approximately 1.0 m deep over a perforated deck. In older units, fans operate intermittently and ventilate the grain by creating a suction on the bed. These fans are connected to a shared humidification system. In more recent Saladin box designs, each bed of germinating grain has a dedicated fan that acts as a blower coupled with a humidification and refrigeration unit. Ventilation in these systems is continuous. The germinating grain is visible in the Saladin box, and germination conditions are easy to control. The uniform depth allows consistent ventilation throughout the grain bed. However, germination is dependent on the conditions within the space itself.

Therefore, the space in which germination is to take place must be adapted to meet the conditions necessary for the process to occur, a task that requires the proper insulation as well as the appropriate dimensions. For a box capacity of around 30 t, the ceiling of the room should extend to a height of 3.70–4 m above the deck in the box. The ceiling should be smooth and constructed without supports to enable air to flow freely from the room without resistance. Insulation prevents condensation of water and mold formation on the ceiling. In some instances, ceilings may be heated.

Several Saladin boxes can be arranged in a germination hall; however, placing each box in a separate space offers the advantage of allowing the accumulation of CO_2 in the recirculated air, since the sliding valves can form an airtight seal. The germination box itself is always rectangular. To achieve uniform ventilation, the ratio of length to width should be 4–8 : 1. Very long and narrow boxes are inefficient, since ventilation is less likely to be uniform. Some designs attempt to compensate for this shortcoming by reducing the space underneath the deck through an upward slope of the floor.

Depending on the loading height of the grain bed, the side walls of the box are between 1 and 1.5 m high and consist of masonry or reinforced concrete. The interior walls must be completely even and smooth, so that as few rootlets as possible are broken off, and no clumps are able to form. For this reason, and for ease of cleaning, the box walls are often lined with stainless steel panels. A toothed bar or a cam rail is attached to the upper edge of the side walls to allow movement of the carriage for the turning device. The rails, as the rollers on the carriage, should be made of a quality of steel that does not rust, such as stainless steel. The interior wall at the front of the box features semicircular depressions equivalent to the diameter of the vertical turning augers. This is to provide the turning augers with complete access to the germinating grain located at the ends of the box.

In some unloading systems, one of the front walls is made of a steel panel which can be moved.

The deck is positioned 0.4–2.5 m above the actual box floor. This distance depends on the size of the box and is also determined by other aspects, such as ease of access to the deck from below for cleaning. The support deck is made of galvanized steel or stainless steel, which is divided into hinged sections, around 1 m^2 each. The deck is perforated with slotted openings, which give the deck a free space area of around 20%. The slots are oriented perpendicular to the movement of the turner assembly. The openings must be kept free by cleaning thoroughly and by the design of the turner; otherwise, the kernels will grow together, causing the piece to become warm. For this reason, the germination deck must be completely horizontal. In every kind of box design, the air for ventilation enters the space between the deck and the floor. The floor of the box is sloped to allow rapid runoff of the water. The water flows into high-capacity drainage channels which are able to be opened and closed.

The germination box can be loaded at a bulk density of 300–500 kg/m^2. This corresponds to a bed depth of 0.7–1.25 m of green malt. Since the bed of freshly steeped grain only reaches a depth of 0.5–0.85 m, additional vertical "air space" to accommodate the grain as it expands and rises must be anticipated when planning and designing germination boxes. The calculation should also include sufficient free space to operate the turning device.

Unlike with a drum, a device is required to turn the piece inside of a germination box. This usually takes the form of a turning machine or carriage. Depending on their width, the boxes may be equipped with 3–15 vertical turning augers according to the size of the system. The vertical augers are set to turn in opposing directions. Their motion, diameter, and angle may vary, allowing them to serve a range of functions, which includes loosening, lifting, and partially turning the grain. To enhance the turning effect, and also to protect the rootlets, the top portion of the vertical auger is made of coiled metal ribbons. Every pass of the turner loosens the grain bed and raises it approximately 10–15%, depending on the stage of germination. Around four passes of the turning device are required to move the lower layers of the grain bed to the top.

A leveler in the form of a U-shaped iron bar is mounted on the turning device at the surface of the grain bed to level it as well as to prevent the formation of clumps. In addition, a rubber wiper is positioned beneath each auger to ensure that the slots in the deck remain open.

The carriage for the turning device is moved by a cogwheel drive system at a speed of 0.3–0.6 m/min. This, in turn, is set at a certain ratio to the speed at which the vertical augers rotate (8–24 revolutions/min) to avoid excessive damage to the rootlets. The speed of the turners is first increased after the grain starts to chit, allowing the grain to be mixed more thoroughly with liquor after it has been sprayed using the nozzles. The pipes upon which the nozzles are mounted must be adequately dimensioned to deliver enough liquor to the germinating grain. The pipes are positioned on both sides of the turning device. The jet of liquor exiting the spray nozzle is aimed at the area surrounding the vertical augers, so that the grain can be thoroughly mixed and the moisture evenly distributed. Each pass of the turning device should increase the moisture in the piece by 3%, whereby the rate of forward movement, the speed of the vertical augers, and the liquor temperature play a role. The carriage and vertical augers are each powered by an electric motor. One motor remains locked when the other is in operation for safety reasons.

A bucket turner is another type of turner used in germination boxes. It turns the grain bed completely in a single pass. Although vertical augers do not loosen the grain bed as much as other types, the turning and mixing effect is more effective, enabling the moisture content of the piece to be increased in a targeted manner through spraying. These designs are similar to earlier devices for turning the malt in the kiln. However, they are more expensive than regular vertical augers. Often, the turners are moved from one germination box to another, something that is not commonly done with vertical augers. While the older bucket turners were only able to function with a shallow grain bed due to stability problems, modern designs are capable of processing grain beds loaded to a bulk density of 500 kg/m^2 (barley in the form of green malt).

Turning is kept to a minimum in order to protect the germinating grain. The grain is turned approximately twice per day during the early days of germination and once per day thereafter. Depending on the design, it may be advisable to turn off the ventilation unit while turning is in progress; otherwise, the air will flow more rapidly through the portion of the grain that has already been turned. However, the temperature rises when the ventilation unit is not in operation, requiring a temperature adjustment to be made either before or after the grain bed has been turned.

In the past, the number of boxes was determined by the number of days the grain underwent

germination. Today, this is no longer the case, since the typical germination period is much shorter, and kilning on the weekends is no longer common.

The capacity of a germination box can range from 5–150 t. Germination boxes have even been designed to accommodate 500 t per unit. Of all the pneumatic systems, the Saladin boxes are the largest in size per unit. As the capacities of the boxes or the systems become larger, their advantages become more apparent.

The temperature and moisture content of the air used for *ventilation of the germination boxes* is adjusted, so that it is suitable for the germination process. Different kinds of ventilation systems are encountered, depending on when the germination boxes were manufactured.

Older Saladin boxes were only equipped with a single suction fan and shared one unit for adjusting the temperature and humidity of the air for the entire system, which consisted of approximately eight boxes. This equipment was usually mounted on the side of one of the boxes. The conditioned air flowed through a large common air duct which was positioned so that it could supply air to the individual boxes. This created a complicated path for air distribution. The air supply was directed into each box through a separate air duct, located on the long side of the box. The air flowed from the duct and entered the space between the box floor and the germination deck through small square openings. It was then drawn obliquely, i.e., unevenly, through the bed upward into a duct mounted on the ceiling of the room where it was then removed. In order to increase the uniformity of ventilation and the temperature of the grain, the airflow was sometimes reversed. This ultimately led to the installation of a combination of suction fans and blowers. The disadvantages of the system were the complicated air distribution network, the tortuous path of the flow of conditioned air, and the distance the air had to travel. Controlling the volume of air via shut-off valves and regulating devices was difficult. This made it virtually impossible to permeate the piece with air with moisture-saturated air. Utilizing air of the same quality for all stages of germination necessitated adjusting the temperature at the inlet based on the coolest piece. This resulted in a high temperature differential between the piece and the air, especially in the stages of advanced growth, which led to further moisture losses in the piece.

The utilization of suction fans arranged as described only served to ventilate the piece periodically. During periods without ventilation, the temperature of the piece was monitored, and when it rose to a certain value within 4–6 h, cooling was carried out over a 2–3 h period of ventilation with an air temperature of 10–12 °C. This continued until the temperature of the germinating grain dropped to a value approximately 3 °C below the temperature at the start of the ventilation process. Thus, the temperatures measured in the upper layer of the piece were 15 °C at the beginning and 12 °C at the end of ventilation during the early days of germination. During the period of most intense growth, they were measured to be 17 and 14 °C. Toward the end of germination, the temperatures were 20 and 17 °C. However, the differences in the lower layer were considerably higher than in the upper layer. The lower layer of green malt was cooled to the temperature of the inlet air within a short time after commencing ventilation. Over the course of the resting period, it even rose a few degrees above the temperature of the upper layer. This frequent temperature change was associated with a high degree of moisture depletion, which could only be compensated for by spraying on the third, fourth, and fifth days of germination. During the unventilated periods, carbon dioxide also accumulated in the piece, reaching concentrations of 5–15% by volume, depending on the length of the rest. The CO_2 levels in the lower layer of the piece constantly remained around 1–5% by volume higher than those in the upper layer. The air introduced through ventilation must not only keep the piece at the same temperature by dissipating the heat generated during germination, but it must also cool it by 3–5 °C using a much higher volumetric output from the fan of 1000–1500 $m^3/(t \cdot h)$ over a 2–3 h period. This high level of ventilation also resulted in further moisture losses in the piece. Once a maltster has learned how to properly monitor the moisture content of the germinating grain and raise it appropriately, malt of a decent quality can be produced in these germination systems. One must keep in mind that the CO_2 content of a piece with intermittent ventilation will be considerably higher than one which is subject to continuous ventilation. Moreover, the corresponding temperature fluctuations caused by such intermittent ventilation will require 1–3% more moisture in the piece compared to other germination systems.

Newer Saladin boxes are much more flexible in this regard. Each box has its own blower as well as its own humidifying and cooling unit. These are situated directly in front of the respective box; therefore, the conditioned air must only travel a short distance through a completely straight duct to flow over the complete distance of the box to the slider valve where the exhaust air is released.

A further improvement is the unobstructed entry of air from the narrow front side of the box to a point directly under the germination deck. The air is able to flow freely through regulating elements spanning the entire width of the box.

However, this arrangement cannot guarantee absolutely uniform ventilation of the piece in the largest boxes (200–300 t). Here, as well as with units with little space underneath the germination deck (refer to Section 1.5.3.3), the box is ventilated in sections from the side with several fans and their respective cooling and conditioning equipment.

The airflow generated by a blower ensures the uniform ventilation for germinating grain leveled to the same bed depth. The volume of air is regulated either by the sliding valve controlling the exhaust air or by flaps in the ducts in front of the fan, i.e., in front of the air humidification system.

The most effective method for regulating fan speed is to utilize frequency-controlled motors. This can take place automatically based on the temperature difference between the upper layer of malt and the air intake. But regulation of the air volume with the sliding valve for the exhaust air is also advantageous because counterpressure can be created inside the germination box by adjusting the valve position to be open, to a greater or lesser extent, or closed. This places the grain bed between two cushions of air, which serves to reduce the loss of moisture in the piece, while increasing the uniformity of temperatures throughout the piece and lowering the volume of air required.

Utilizing recirculated air has also proven very effective for controlling the temperature of the piece. As mentioned above, this method requires a special recirculated air duct, which can be mounted on the ceiling or under the platform of the box in an arrangement with one box per room. A common duct is usually employed for the collection of recirculated air if several boxes are located in one germination hall. When initiating germination in the box, the barley should be held at the same temperature as it was when cast from the steep, i.e., approximately 18 °C. Alternatively, the grain has to be reheated if cold water was employed in transporting the grain from the steeping vessel to the box. This is usually accomplished by means of warmer recirculated air or a temperature-based blend with fresh air. Hardly any CO_2 enrichment occurs inside modern germination boxes due to their relatively large volumetric capacities. The temperature serves as the control variable for the automatic blending of fresh and recirculated air (refer to Section 1.5.3.3), regardless of whether the boxes are arranged individually or grouped together in one germination hall. If a single box is already equipped with a refrigeration unit, a greater proportion of recirculated air can be employed during the final days of germination to limit respiration to some degree. In any case, the recirculated air during summer operation is cooler than the outside air because it also becomes fully saturated with moisture as it cools.

In contrast to the older Saladin box designs, the newer models are continuously ventilated. The fan output is also lower; it varies from 250 to 700 $m^3/(t \cdot h)$, depending on the stage of germination. Continuous ventilation results in a high degree of uniformity in the air temperature within the piece. Nevertheless, the temperatures are lower toward the bottom of the grain bed and higher at the top. The cooler air enters from below, heats up as it passes through the grain bed, and flows out of the top. However, if the ventilation system is properly designed, the differences are small and usually do not exceed 2 °C. If the temperature differential is greater than 2 °C, then the fan output is too low. Should it be less than 2 °C, then the volumes of air being moved are too large. The optimum difference of 2 °C can, for example, be maintained by utilizing frequency-controlled fans.

The *temperature sequence* in a traditional germination regime is as follows: a centrifugal pump is employed in the steeping process to achieve the desired moisture content. As a rule, the temperature of the steeped grain is 11–12 °C. Multiple passes with the turning device level the surface of the grain bed. It is best to refrain from ventilating the grain initially, so that excess liquor can drain off, and the moisture on the surface of the grain can be absorbed. Only when the grain exhibits signs of drying, such as the temperature rising independently to 13–14 °C, should ventilation commence with fully humidified air. With longer resting periods, it may be useful to aerate briefly every 1–2 h (for 10–15 min) in order to remove the CO_2 being generated. As a rule, it takes 16–24 h for the kernels to absorb the liquid on their surface after steeping to a moisture content of 43%. This also depends on the water sensitivity of the barley. Absorption of liquid from the surface increases the moisture content of the kernels by about 2%. The earlier practice of "drying" with non-humidified, attemperated air caused evaporative cooling to occur in the grain bed, subsequently delaying germination.

The germination temperature is increased from 13–14 to 15–16 °C during the first 3–4 days of germination; the temperature in the lower layer of the grain bed is 1.5–2 °C lower than that of the upper portion. In order to promote uniform

growth, turning the piece three times on the third to the fourth day of germination is recommended. Easily modified barley is held at 16–17 °C until it has finished the germination process. Barley that is resistant to modification is germinated at 19–20 °C for a period of 7 days. Therefore, the incoming air must be preheated accordingly to accommodate the rising germination temperatures. It is necessary to adjust the temperature of the incoming air on a daily basis by varying the blend of fresh air and recirculated air. The proportions depend on the day of germination, the progression of growth, and the degree of modification. During later stages of germination, given an ample fan capacity, the intervals between turning the piece can be extended from 12 to 16 h and up to 24 h. As the turning device moves through the piece – even with constant ventilation – the temperature of the germinating grain rises by 1–2 °C. This is due in part to dissolution of the heat islands within the piece as a result of non-uniform ventilation. Primarily, however, the increased air influx into the areas that have been turned induces stronger respiration and thus heat generation within the grain bed.

Warming the air, even if it is only 2 °C, coupled with the movement of air, draws moisture out of the piece, making it necessary to spray it after about 4 days of germination. For this purpose, and also for the sake of a targeted increase in the moisture content of the piece, the turning machine carriages are equipped with a system of spray nozzles on both sides to apply liquor either before or while turning the grain. Stationary spraying systems may also be mounted over the germination bed. However, they do not fulfill their purpose entirely because the "mixing effect" of the turning device is lacking. In general, the moisture content of the green malt can be increased by approximately 2% with a single pass of the turning device. The moisture content of the piece decreases by about 0.5–0.7% per day if there are no major fluctuations in temperature (e.g., cooling down after more intense heat generation).

As the kernels grow, their rootlets become interwoven, which is known as "felting." This occurs during germination in traditional floor malting. The kernels are not given this opportunity in the germination box. Only the kernels in the upper layer felt slightly if ventilation is intermittent, or if the grain bed is only turned at longer intervals. The accumulation of CO_2 in the lower layers of the bed prevents this from happening. Likewise, continuous ventilation does not allow condensation to form on the surface of the grain because the moisture released through respiration is immediately carried away by the air flowing past. Special attention should be paid to the formation of clumps; this can occur along the side walls of the box, especially in the semicircular depressions in the wall on the front side of the box, and also in any area of the piece that may become too warm.

A standard temperature regime for a germination box is described in Table 1.9.

Germination at falling temperatures: modern steeping methods, such as pneumatic steeping, yield uniformly chitting, sometimes partially forking, kernels after 48–52 h. The grain temperature is 15–18 °C with a moisture content of 41–42%. If the equipment and conveyor systems facilitate casting out the steeped grain "dry," it must be immediately ventilated with conditioned air. The most common practice is to cast the steeped grain out "wet." Despite the higher temperatures mentioned previously, the grain is left to drain for a few hours, since an immediate, intense ventilation process would interfere with excess steep liquor flowing out of the grain bed. Ventilation (with conditioned

Table 1.9 A germination regime with rising temperatures.

Germination period	[d]	1	2	3	4	5	6	7
Temperature								
Grain bed, top	[°C]	12	13.5	14	15	16	17	18
Grain bed, bottom	[°C]	12	12	12	13	14	15	16.5
Ventilation air		–	11.5	11.5	12.5	13.5	14.5	16
Fresh air	[%]	25	75	75	60	50	40	30
Recirculated air	[%]	75	25	25	40	50	60	70
Moisture (green malt)	[%]	42.5	45	44.5	44.0/46.0	46	45.5	45
Fan output	[m^3/(t·h)]	300	350	450	500	500	430	370
Turning interval	[h]	12	12	8	12	16	20	24

air) commences as soon as the temperature in the piece rises. Simultaneously, the temperature of the steeped grain is maintained at 15–18 °C until the maximum level of moisture is achieved through spraying. Only then is the piece cooled to 12–14 °C; this temperature is maintained throughout the rest of the germination period.

Depending on how the temperature sequence is carried out along with the level of moisture selected for the grain, it is possible to adapt the germination conditions for different types of barley or malt. The result is a higher extract yield, better modification, and a higher level of enzymes, which is reflected in the values obtained in the VZ 45 °C mash method and for α-amylase. The germination period can usually be shortened as well, as described in Table 1.10.

The moisture content of the freshly steeped grain including the liquid adhering to the surface is 42.5%; this moisture content is maintained until all kernels start to fork evenly (after 20–24 h). The first application of liquor through spraying increases the moisture content to about 45%, followed by another 24 h later, which brings it up to 48%. At this point, the piece undergoes intense cooling. The smaller volumes of air flow during the modification stage only cause a slight decrease in the moisture content.

A pneumatic immersion steep on the second day – especially in the warmer seasons or if there is inadequate access to the steeping equipment – has quite often been shown to be difficult to control (refer to Section 1.3.6.2). Also, kernels that are forking or even partially forking can experience "water shock" when cast out wet, which is intensified by the pressure on the grain in the conveyor as it is transported to the germination unit. For this reason, it is often much more advantageous to forgo the second wet steep after approximately 26 h and to cast out the grain from the steep when it has reached a moisture content of around 38%. After germination has commenced under precisely defined conditions, e.g., 18 °C, the grain can be sprayed for the first time. Once the kernels have evenly forked, the grain can be sprayed a second time. A maximum moisture content is reached once 12 h have elapsed. After this 48–60 h phase, the temperature is lowered as described previously. Despite the loss of 1 day of steeping, the seamless transition of the individual stages usually allows a germination box occupancy rate of 6 days. It is important, however, to ensure that the moisture content of the grain is increased by 8–10% through spraying two to three times within this 48–60 h period. To achieve this, it is helpful to use heated liquor (18–22 °C) for application onto the grain along with a suitable arrangement of spray nozzles. The turning device should make two passes each time the grain is sprayed. The liquor should only be applied in one direction to create uniform conditions for moisture uptake by the grain. The third spraying procedure is carried out with cold water to begin cooling the piece.

The effect of the spray nozzles can be enhanced by "pulsing," which is also helpful when "flooding" (or inundating) the grain with steep liquor. The carbon dioxide concentration of the air in the piece can increase if individual boxes are in separate rooms. CO_2 concentrations of 4–8% can be achieved if the sliding valves or the like are tightly sealed. CO_2 at concentrations of 3–4% somewhat suppresses growth during modification and serves to reduce malting losses. This is possible while still adhering to the guidelines of trade associations, such as those for maltsters in Germany. Also, the process of germination is easier to control when the grain is not cooled too drastically. However, increasing the CO_2 concentration to as high as 8–10% too early in the germination process is detrimental to modification and the enzymatic

Table 1.10 A germination regime with falling temperatures.

Germination period	[d]	1	2	3	4	5	6
Temperature							
Grain bed, top	[°C]	18	18	18/13	13	13	13
Grain bed, bottom	[°C]	16.5	16.5	16/11	11	11	11
Ventilation air		16	16	15.5/10	10	10.5	10.5
Fresh air	[%]	80	70	70	30	20	20
Recirculated air	[%]	20	30	30	70	80	80
Moisture (grain)	[%]	42.5	42.5/45.0	45.0/48.0	48	47.7	47.5
Fan output	[m^3/(t·h)]	350	500	500	400	350	350

capacity of the malt (refer to Section 1.4.1). Lowering the fan speed in order to move smaller volumes of air toward the end of germination not only saves energy and reduces malting losses, but it can also improve some analysis results, such as those attributes measured in the VZ 45 °C isothermal mash.

Controlling the germination process as it occurs in the piece can be automated through the application of refrigeration and – in the colder season – through temperature-dependent regulation of the flaps regulating the fresh and recirculated air (refer to Section 1.5.3.7). However, operations involving the extensive utilization of recirculated air, which is only put into practice in rooms with high ceilings, possess the advantage of simpler automation and the ability to achieve the desired concentration of carbon dioxide in the ambient atmosphere of the room. The associated savings in malting losses are offset by the slightly higher energy costs during the seasons of transition as well as in the winter.

The *resteeping process* can only be used with germination boxes suitable for such operations. It requires a sufficiently sturdy box construction to withstand the additional weight of the resteep liquor. The box must also be waterproof, with fans mounted at higher positions or sealed off with a system of water locks. After steeping for close to 1 day, the moisture content of the grain reaches approximately 38% in the germination box. The grain germinates very quickly and evenly at temperatures of 16–18 °C, but root development is minimal due to the low moisture content. The entire box is flooded after about 48 h of germination. Depending on the temperature of the water (12–18 °C), the resteeping period ranges from 24 to 8 h. The colder the water is, the more time is needed to "inactivate" growth. Subsequently, the germinating grain undergoes a 48–60 h period of modification. Resteeping raises the moisture content to 50–52%. At this level of moisture, modification proceeds rapidly and to a great extent, even at the lower temperatures of 12–14 °C. Rootlet growth will always be minimal. On the other hand, development of longer acrospires is favored by a longer modification period, to the extent that even huzzars may occur. Malt produced in this way is also rich in enzymes, although some of the exoenzymes (peptidases and glucanases) are diminished. Malt losses amount to 5–6%, d.m., if the germination procedure is carried out properly.

A kind of "resteeping effect" can also be achieved in standard germination boxes. At the time scheduled for resteeping, the turning device is passed through the grain bed two separate times in the same direction. As the grain is turned, it is simultaneously doused with steep liquor which is sprayed at full force from the nozzles. After the first pass is complete, the second pass is carried out approximately 150 min later. In this way, the moisture content of the piece can be increased from 38% to 50–52% over the course of 12–14 h by means of 4×2 turning passes. This method yields malt analysis results that are similar to those from malt produced with conventional resteeping methods, with only slightly higher malt losses. Simply "inundating" or dousing the germinating grain with large volumes of water, or even recirculating the water inside of the box with pumps, is useless without the mixing effect of the turning device, since only then will every level of the grain bed be exposed to the same amount of water. Although the resteeping technique is associated with certain advantages, such as accelerating germination and reducing malting losses with controllable malt quality, the necessity of removing approximately 6% more moisture through drying has proven to be simply infeasible. Further disadvantages include the additional volume of wastewater and the inability to reuse the water from the steeping process.

The methods described above demonstrate the adaptability of modern Saladin boxes with their dedicated ventilation and refrigeration systems as well as the various options they are able to offer.

Transferring the green malt from the germination box to the kiln should be possible within several hours (2–3 h), even in very large units. A mechanical transport system for green malt consists of a green malt elevator and screw or drag chain conveyors (Redler conveyors). The green malt is moved either by winch-drawn *power shovels* (bucket scrapers) or by a mobile device designed for clearing green malt from the box. Since the original quantity of barley to be germinated, e.g., 100 t, has a green malt weight of 150–160 t due to its moisture content, the equipment must have the capacity to move 50–80 t/h in order to load the kiln within a reasonable time. Winch-drawn power shovels require too much manpower (2–3 people); the physical labor is exhausting with large germination boxes. *Clearing machines* are only economical in germination halls; they require retraction of the carriage of the turning device, so that the clearing machine can move the green malt out of the box. Its operation requires only one person. The newest and most economical solution, which also keeps pace with the size of the boxes, is a *machine capable of turning and clearing the box*, which typically moves at a speed

of 0.4 m/min. It works in a specific area of the piece, pushing it in portions at a rate of 10 m/min into the trough for green malt transport. It is fully automatic and only requires monitoring. With the pneumatic transport of green malt, shoveling the green malt into suction funnels or spouts was considered too labor-intensive. The *Koch clearing system* takes advantage of the lifting effect of the helical spirals as they turn. They lift the green malt into the transverse screw, which in turn pushes it into the receiving end of a telescopic suction tube. Large transport capacities are possible with this system as well, with just a single man necessary for positioning the tubes in the bed. The so-called "clearing sets" are based on similar principles and can be easily fitted to the existing plants. Also of interest – primarily for mechanical transport – is the *transposal deck*, which slowly pushes the green malt into the trough positioned alongside the box. The trough runs either along the floor of the box or over the box ceiling and can be cleaned automatically by various means. If the steeping vessels are positioned accordingly, it also allows "dry" casting of the steeped grain.

Germination boxes, along with their decks, turning devices, and spraying towers with their ductwork, must be cleaned with care. This task can be simplified through the installation of high-pressure spray jets. Motor-driven cleaning carriages automatically clean the area underneath the germination deck with caustic solution and subsequently rinse it. Two parallel units are required for cleaning support structures. A similar type of carriage can also be used for cleaning the portion of the box above the deck. This type of cleaning machine is rather expensive; therefore, most malt facilities use them to clean several germination boxes. However, this requires movable front panels on the boxes as well as a transverse connection from box to box. Machine maintenance should include the fans, the turning mechanisms, and the refrigeration system.

Other types of pneumatic malting plants are essentially all more or less based on the same principle as the Saladin box: the *Wanderhaufen* malting plants, which enable a horizontal and vertical movement of the piece (transposal), or "stationary" systems, in which all process steps take place in a single unit: steeping, germination, and kilning.

Round germination boxes, either situated on the same level or built one above the other ("germination towers"), were originally designed and operated as such (refer to Section 1.6.2.3) until the years of the energy crisis. At this point, the kilning process was separated for the sake of energy recovery. Systems created since the 1980s serve the exclusive purpose of germination. They are made of concrete using the formwork construction technique in sizes up to 600 t/unit, with specific loading rates between 450 and 580 kg/m^2. The germination decks are made of stainless steel, and the space under the deck is lined with stainless steel to facilitate cleaning. The decks are either fixed with a rotating turning unit, or the decks rotate with a stationary turning unit. The rotary decks are moved by several gear motors on the periphery along a gear ring. For example, the decks can be moved at two rotation speeds of 60 and 120 min/rotation in either direction. Germinating grain or green malt can be spread or cleared from a deck area of 300 m^2 through this rotating motion. For rotary decks, the integrity of the seal between the deck and the wall of the building is of great importance. The estimated peripheral rotational speed of the external edge of the deck should not exceed 0.55 m/min when the grain is turned. It drops to 0.15 m/min down the length of the turning carriage to the center. For this reason, the rotational speeds of the turning screws must be reduced from 12 rpm on the outside to 3.5 rpm at the inside in order to avoid excessive rootlet breakage or even damage to the germinating grain. A loading and unloading device with a transverse auger (in the form of a centerless auger in the inner third), which can be raised and lowered, is attached to the turning device. This allows each loading or unloading process to be completed within 2 h.

A more recent development is to build round, single-story units from prefabricated wall elements. These are already finished on the edges, painted, and can be assembled to create a cylindrical building. All the necessary openings and recesses in the individual elements are already in place, for instance, for connecting the wall elements to each other, for their connection to the base plate and the roof segments, and for mounting fixtures. The curved wall elements are screwed together according to the container diameter and covered with sheets of stainless steel. The resulting cylinder is stabilized by the base plate and by a ring under the eaves. The deck substructures and the decks are then inserted into the finished cylinder before the roof segments are installed. The turning assembly with spreader and unloading auger is inserted before the last roof segment is set in place. The structure is then insulated.

The ventilation equipment is housed in a building enclosure located on the side of the germination tower and features a staircase and an elevator shaft. Axial or radial fans provide ventilation;

usually two are needed for larger germination units. The ventilation systems are dimensioned to provide a maximum output of 600 m^3/(t·h) and are frequency controlled to allow stepless adjustment to any speed lower than the maximum. The capacity of the cooling units is 10,500 kJ/(t·h) or 2500 kcal/(t·h). Humidification of the intake air is imperative despite the use of recirculated air (the arrangement of the recirculated air ducts is structurally complex).

Germination takes place in round boxes – whether situated on the same level or built one above the other – according to the same principles as in rectangular units. Often, 2 days are devoted to steeping in conical steeps. Alternatively, the grain is steeped for 1 day in a group of conical steeps and 1 day in a flat-bottomed steep; germination is generally estimated to require 6 days or, less often, 5 days.

Larger germination plants are cleaned with pressure sprayers using cold and hot water or by means of an automatic cleaning system installed in each box, which is also capable of cleaning with caustic (sodium hydroxide) solution.

Automatic cleaning is easier for rotary germination decks, especially for reaching areas beneath the deck, since the cleaning equipment installation is permanent.

Robotic equipment, powered by batteries or electric motors, can be employed in large germination facilities, such as in towers. A swivel arm, equipped with nozzles, cleans the requisite surfaces with high-pressure water. Cleaning and disinfection agents can be added as well. The cleaning equipment is fully automated. However, the duration of cleaning does potentially raise an issue regarding time, since together with the time required for loading and unloading, it will inevitably curtail the time allotted for germination. Furthermore, one should note that malt is a foodstuff and is therefore subject to the mandatory hygiene guidelines regulating the handling and processing of food.

1.5.3.4 *Wanderhaufen* Transposal Malting Systems The *Wanderhaufen transposal malting system* comprises a number of germination boxes attached to one another longitudinally in a single line. One germination line consists of seven to nine boxes, each of which is divided into two half-day boxes to create 14–18 individually ventilated compartments. Over the course of the process, the germinating grain migrates from the first half-day box all the way down to the last one. From there, the green malt is either transferred by means of a conveyor to the kiln, or the turning device moves the green malt through a temperature lock to an identical deck just beyond it for kilning. The floors of the transposal system consist of the decks standard for germination units or of slotted screen decks. *Ventilation* of the system can be accomplished longitudinally or laterally. *Longitudinal ventilation* comprises two fans and two cooling towers for each germination unit. One fan and one cooling tower are dedicated to one type of air quality, usually, either fresh or recirculated air. The ducts for both types of air run parallel to the germination unit and are mounted one above the other. The desired temperature in the half-day box can be reached by blending air of both qualities using a gate valve, after which it is delivered to the compartment. In *laterally ventilated systems*, the ducts supplying the air run perpendicular to axis of the germination line. For this reason, the cooling and conditioning equipment is located on the long side of each unit in the line. There are two distinct types: the individual cooling towers for supplying a unit designed for a single day of germination and centralized air treatment for the entire line. In the latter case, the streams of fresh and recirculated air are separated, purified, attempered, and then moistened. From there, the air passes through a second cooling unit in which fresh air and recirculated air are blended according to the conditions in the individual germination units. The second cooling unit can vary in size and have the capacity to cool several days' worth of germinating grain simultaneously (day 1, days 2/3, days 4/5, and days 6/7/8). Lateral ventilation systems supply air to several germination lines situated parallel to one another.

Turning devices in *Wanderhaufen* systems fulfill the dual function of turning and conveying the grain. The piece is automatically moved to the next half-day unit each time the grain is turned. If the kiln directly adjoins the germination line, the turning device must cover twice the distance, which can be achieved through the appropriate damper settings. The turning device consists of a frame on a carriage which moves forward at a speed of 0.33 m/min while it is turning; when idle, the device can move at around eight times this speed (2.5 m/min).

A triangular bucket elevator capable of operating over the entire width of the box is suspended in the carriage, which can be hydraulically raised and lowered. The bucket elevator is inclined on the receiving flank, so that it is set to correspond to the mean angle of repose of the barley. This grain is then transferred precisely one half-day unit further in the opposite direction of the turning device.

Turning must be carried out twice a day in order to free up the space in the first two half-day units for the grain being cast from the steep. The kiln is loaded once per day; i.e., two pieces must be removed at the same time. The turning operation starts at the end of the germination line, which is loaded with finished green malt, and proceeds to the beginning, the first unit where the grain freshly cast from the steep is located. Each turning device must have sufficient power to operate on three to four germination lines. Turning in the Saladin box is accomplished in a different manner: a triangular paternoster (vertical carousel conveyor) produces a tossing motion similar to that used in floor malting. However, this motion does not create new layers; rather, it thoroughly and uniformly mixes the piece. The angle of repose formed by the falling grain is the opposite of the one used by the paternoster to scoop up the grain. This causes a zone where mixing occurs to form at the interface of the two pieces. The angle of repose on the side being scooped up remains constant, while that on the falling side is dependent on the moisture content and the amount of growth in the green malt. It ranges from 44° for a wet piece to 65° for a young or old piece. The extent of the zones of mixing on a germination line is around 35%.

For reasons of stability, the turning device described above is limited to a maximum box width of 5.6 m. This also restricts the daily output to 15 t per germination line. Newer turning devices with screw conveyors lying next to one another allow for a greater width, thus increasing the daily output to approximately 50 t. The mixing of grain at different stages of germination occurs to a lesser extent in this case because the angle of repose that forms on the grain being scooped up is no longer opposite to that of the grain being tossed or that is falling.

The germination conditions in the *Wanderhaufen* are comparable to those in a germination box housed in a germination chamber. The temperature difference between the uppermost and lowest layers is 1.5–2 °C. Due to the mixing that occurs, it is advisable to raise the temperature in the piece to 17 °C on days 3/4 of germination in order to achieve decent cytolytic modification. The conditions with regard to the moisture content are also similar to those found in a box malting plant. It is possible to cast out the steep dry. The moisture content of the germinating grain can easily be increased incrementally due to the intense mixing effect, particularly with a screw auger. An accumulation of CO_2 in the piece is not possible, given the conditions in the germination chamber. The *Wanderhaufen* method produces flawlessly modified malt. The primary advantage of this method is the simple operation and limited amount of manual labor required. Individual air treatment devices allow for the automatic regulation of temperature.

1.5.3.5 Lausmann Transposal Germination Systems The *Lausmann transposal germination system* is also known as a *Wanderhaufen* system, a German term that refers to the fact that a piece of steeped barley is moved, or wanders, as a unit fresh from the steep to a series of germination boxes. The piece moves from one box to the one directly adjacent to it and so on until germination is finished. The germination boxes have square or rectangular false decks, which can be raised and lowered. The movement of the decks was carried out in older systems with hydraulic cylinders filled with water or oil. In more modern systems, this is implemented through usage of synchronously driven gear drives, which guarantee steady horizontal movement of the decks even in larger systems. By lifting the deck, the germinating grain is lifted above the partition separating it from the adjacent germination box, and by means of a specially designed turning device, the piece is moved into the next germination box or into the kiln. The turning device, based on the design of a scraper conveyor, is equipped with an extension which is able to reach across two germination boxes, so that the germinating malt cleared from the previous box is completely in level with the one in front of it. The deck loaded with germinating malt is lowered. By gently removing, for instance, 20 cm off the top, this serves to destratify the piece by turning it over thoroughly. The turning of the piece, however, results in a certain amount of compression in the first third of the germination box, which allows less air flow as a consequence. If more is removed each time, for example, 70 cm, this reduces the compression and facilitates more uniform ventilation. Nevertheless, it still takes some time before the higher temperatures present in the first third shifted over to the next box become more evenly distributed throughout the bed. In more modern systems, this can largely be avoided by slightly tipping the half of the deck with the somewhat higher bed of germinating barley. This kind of adjustment is also required when loading an attached kiln, apart from the fact that the area of the kiln deck has to be 75% larger than that of the germination box. The kiln deck should be loaded at a rate of 600–620 kg/m^2.

The grain bed is not densely packed because it has been turned, as described. This allows the

Table 1.11 Fan and evaporator settings in the boxes of a *Wanderhaufen* system.

Boxes		1	2	3	4	5	6
Fan output	[m^3/(t·h)]	450	600	750	750	600	450
Evaporators	[kcal/(t·h)]	1500	2000	2500	2500	1500	1000

grain to be turned only once per day. Concurrent spraying by ample rows of nozzles enables the moisture content to be increased in the germinating grain by up to 6% each time it is turned. The evolution of heat in the grain is quite pronounced on the second, third, and fourth days of germination. This must be considered in designing the fans and evaporators. However, in this case, as with the *Wanderhaufen* (refer to Section 1.5.3.4), on each day of the process, a specific stage of germination takes place. The data listed below can be taken as a basis for ventilation and cooling over 7 days of steeping and germination.

The fans are fitted with dual-speed motors that can operate at ⅔ their normal speed if less ventilation is required. Modern, large-scale systems have fans equipped with variable frequency drives. Since the lifting cylinders are placed sufficiently deep, e.g., in boxes two and three, the deck can be lowered so far that resteeping can be carried out there with relatively little water usage. The various techniques built into these systems for rapidly moistening the grain serve a purpose similar to the one outlined in Section 1.5.3.3. A network of large nozzles allows large volumes of liquor to be sprayed over the grain in 15–25 min. Nevertheless, no means exist in these systems for producing the effect of simultaneously turning the grain because this kind of rapid moistening is not efficient enough. Boxes with a capacity of up to 60 t are built for modern facilities. They can be operated economically and are able to comply with a range of settings for the germination parameters. Only the carbon dioxide ratios correspond to those of the germination chamber (Table 1.11).

1.5.3.6 Other Malting Systems *Other malting systems*: up to the seventh edition of this book, a number of malting systems that had been developed in the 1960s and 1970s were discussed. Because of their small batch sizes, these are now generally obsolete, including the germination tower (Optimälzer) or combined steeping/germination/kilning vessels (e.g., the Popp system). They have certainly made a valuable contribution to the current understanding of malting technology. Information about these older malting systems is available in earlier editions of this book.

The method according to Kropff, in which a "carbon dioxide rest" was performed, is also no longer current because it required construction of a uniquely designed container, called a "modification box." After about 4 days of traditional germination, the grain was subjected to two to 3 days of a "carbon dioxide rest." This required that the carbon dioxide atmosphere be removed twice daily in order to avoid "intramolecular respiration" with decomposition of the endosperm. Around 2–4% of the malting losses were able to be prevented; however, loading and emptying the "Kropff box" was quite labor-intensive. The volumetric capacity of the box was limited to around 15 t. The classic method for operating this kind of system was also described in detail in earlier editions of this book.

Focused, proportionate enrichment with carbon dioxide at a rate of 4% in single-box germination vessels is feasible even in larger systems (refer to Section 1.5.3.3).

1.5.3.7 Modern Static Systems *Modern static systems* are currently available. The two described below operate according to different principles. A combination germination and kilning drum receives grain cast from a steep mounted on the drum itself (refer to Section 1.5.3.2). The method of operation is described in the aforementioned Section. Withering and curing in this kind of system are based on the principle of a single-deck kilning. Both light and dark malts can be produced in the drum, which also allows for the production of caramel malt. Malting systems of this kind are currently available with capacities of up to 10 t/drum.

A single vessel can also be used for steeping, germination, and kilning. The device is equipped with the standard systems for treating the air for steeping and germination as well as with a helical turning device. An air heater is also included for kilning and is capable of serving several of these kinds of

systems. Both light and dark malts in addition to various types of caramel malts can be produced in these vessels.

1.5.3.8 Employing Starter Cultures As has already been described in Section 1.4.1.8, barley and other kinds of maltable grains harbor more or less thriving communities of microflora, the condition of which depends largely on the climate conditions during grain cultivation and harvest. In order to quell the "stocks" of molds, bacteria, and yeasts, treatment of the steeping and germinating grain with starter cultures, comprising certain lactic acid strains of bacteria, is recommended. The lactic acid fermentation induced by doing so is already employed in the food industry for the natural preservation of food both for human consumption and for animal feed. Additions of starter cultures containing *Lactobacillus plantarum* and *Pediococcus pentosaceus* during application of the first and second steep liquor in quantities of 4% and 8%, respectively, achieve a reduction in the number of *Fusarium*-infested kernels. The concentrations of mycotoxins, such as zearalenone (ZEN) and deoxynivalenol (DON), thereby decline. The yeast species *Geotrichium candidum* produces a similar effect. It is important that the starter culture be added in the steeping vessel, since the grain's inherent microflora proliferate and multiply very rapidly there. In addition to molds, growth of bacterial flora is also curbed. The well-known strain *Lactobacillus amylolyticus*, which excretes its own extracellular enzymes, brings about an especially beneficial effect. The enzymes of the native microflora compete with those of the starter cultures, but ultimately, the microbes in the starter cultures dominate.

In summary, the following has been observed regarding this concept, which is still in development:

Starter cultures can be isolated and propagated from cereals or the malt produced from them. Once inoculated with the starter cultures, hygienic conditions during steeping and germination improve significantly. Results from malt analyses are more favorable, and malting losses are lower due to suppression of rootlet growth caused by the (extremely slight) pH reduction in the piece. A decline in the tendency for malt to induce gushing in beer has not yet been established for the sole reason that an insufficient amount of evidence has been gathered thus far.

1.5.3.9 Stimulating and Inhibiting Germination Using *special methods to influence germination*: a distinction is made between germination-inhibiting substances and those that serve to stimulate growth (auxins).

Due to the *Reinheitsgebot*, substances that inhibit germination are of no relevance in Germany. Applying nitric acid or urea nitrate inhibits the growth of the rootlets. However, this is now only of historical interest. Outside of Germany, potassium bromate (100–300 mg/kg barley) can now be employed for this purpose and again later as a protease inhibitor. An addition in the final steep liquor reduces malting losses by about 2% by suppressing protein modification. The flush steep method, for instance, can also be used to check intense growth.

The addition of enzymes, such as endo-β-glucanase, improves the cytolysis in barley exhibiting sluggish modification (multi-rowed winter barley). However, the glucanases, which are obtained from fungi that cause mold, are added only on the last day of germination or even by means of a dosing auger when the piece is being cast from the germination box. Since these enzymes are more stable than the kernels' own enzymes, they are in full effect during mashing as well.

Gibberellic acid is one of the *substances capable of activating germination*. It is also present in the germinating kernel. Auxins added in amounts of 0.01–0.25 mg/kg barley induce the rapid and heightened formation of enzymes. As a consequence of more pronounced enzyme induction, the finished green malt displays very advanced cytolytic and proteolytic modification. Germination normally lasts 7 days but can be curtailed to 4–5 days. Especially with higher additions of enzymes, the profusion of low molecular weight degradation products results in excessive color development during kilning. The most logical approach is to add gibberellic acid to the steep liquor. However, $2\frac{1}{2}$ times the amount is required in the steep liquor in order to achieve the same result, when compared to the amount necessary if applied through spraying after the steep has been cast into the germination box. Small amounts (0.01–0.03 mg/kg) serve to improve barley slowly to undergo modification, while doses of 0.06–0.10 mg/kg applied in the germination box curtail germination. With a germination period lasting 4–5 days, the changes in the malt remain within their normal parameters, including the color of the Congress wort. And yet, the boiled wort color (refer to Section 1.8.3.6) increases notably even if treated with smaller doses, compared with untreated malt; 0.15–0.25 mg/kg can be utilized to compensate for a lack of germinative energy

in barley. Auxins do not reduce malting losses, unless it is only by very little. Conversely, a combination of 0.25 mg of gibberellic acid and 100 mg of potassium bromate per kg of barley can indeed mitigate the losses experienced during malting and can concretely influence modification while also curtailing the germination period. Gibberellic acid also confers technical advantages when applied in combination with a resteeping step at 40 °C.

Of particular interest is the use of gibberellic acid after the barley has been slightly abraded, which removes 0.5–1.0% of the husks. Breaching the pericarp and testa can result in even greater penetration of the gibberellic acid into the interior of the kernel, accelerating enzyme formation and modification. Damage to the pericarp and testa can also improve the malting properties of freshly harvested barley. The germination period is reduced by 40–50%. One disadvantage, besides losses to the substance of the kernel, is that the degree of modification during germination is very difficult to estimate. The extremely intense enzymatic activity may cause overmodification later during the withering process. It is best to stop germination when it is most appropriate to do so; for instance, this can be done with a combination germination and kilning system. The grain can be damaged very easily during transport. This process is further accelerated through application of slightly acidified steep liquor (approximately 0.01 N H_2SO_4).

However, it has been shown that removing 1–2% of the mass of the barley through polishing – even without a gibberellic acid addition – is ultimately positive. This eliminates the water sensitivity to a large extent, in addition to encouraging rapid, intensive growth. Enzyme development is vigorous, and the resultant enzymatic activity is strong. The germination period is reduced by at least 24 h as well. Abrading the husks results in a higher extract yield (which even permits the utilization of multi-rowed winter barley) and high levels of modification. This also gives rise to more intense color formation, which also occurs in combination with gibberellic acid. The industrial abrading machines currently available can process barley at a rate of 8 t/h. Most important regarding this process is that *all* the kernels have to undergo the abrading process. A considerable amount of development remains to be done with regard to this process.

Crushing the barley steeped to a moisture content of 37–39% (two-roller mill with a roller gap set to 1.8–2.0 mm) exerts a force on the cells of the aleurone layer and the endosperm. This causes damage to the structural elements supporting the cell walls. Immediately after the grain has been crushed, steep liquor and gibberellic acid (0.25–0.75 ppm) are added. They are, as a result, more evenly distributed throughout the kernel. Five days of germination at a moisture content of 40% produces malt that meets the desired specifications. Without the gibberellic acid, the process does not produce satisfactory results, in spite of the higher moisture content during germination.

Gibberellic acid additions in malt production are not permitted in Germany. It can be detected by means of immunological methods in the most minute doses.

Adding a sugar solution toward the end of germination represents one method for improving malt. The so-called "glucose" malt treated in this manner produces higher extract values and improved modification characteristics.

The various developments involved in resteeping the grain must also be counted among notable germination techniques (refer to Section 1.5.3.3). Resteeping for 3 h at 30 °C greatly curbs the growth of the rootlets. Curtailing the steeping and germination periods to a total of 96–110 h is possible with resteeping, while also reducing the malting losses to only 4%.

Combined with gibberellic acid, reducing the duration of steeping and germination to 84–96 h is feasible through the use of a procedure comprising multiple steeping rests, if the steeping temperature is 40 °C. This results in the suppression of rootlet growth and leads to a corresponding reduction in the malting losses. The changes in the kernels can be controlled, firstly, by the concentration of gibberellic acid and, secondly, by dimensioning the warm liquor steep, which controls the level of inhibition in the grain. These kinds of techniques make moving or turning the germinating grain unnecessary. For this reason, they are primarily applicable in static systems, i.e., those without turning devices.

1.5.4 The Finished Green Malt

At the end of the germination process, the green malt must be assessed according to its appearance and the properties of the substances inside of the kernel. This makes it possible to draw conclusions regarding how the malting process progressed and whether the measures applied were appropriate.

Green malt should smell fresh with an impression similar to cucumber. A sour, fruity odor is a sign of improper handling of the barley (storage of spoiled kernels) or poor practices during steeping

(oversteeping and intramolecular respiration) or germination (inappropriate resteeping techniques, spraying too frequently, an excessive CO_2 rest with less-than-adequate intermittent aeration, and inconsistent ventilation of malt on the deck in the kiln). A musty, moldy odor indicates that barley contaminated with fungus was processed, that the barley was insufficiently cleaned in the steep, or that a secondary infection occurred during germination. The last is rare unless the barley being processed exhibited an excessive number of damaged kernels, or that the barley was abraded or crushed through handling. Even kernels that are split open are subject to infection with molds. A dull, stale odor can also arise from the presence of a high proportion of rootlets that have broken off of the kernels of green malt and have settled between them, which makes it difficult to force air through the bed in an even manner.

For this reason, the appearance of the germinating kernels, i.e., the green malt, must be monitored daily. Particular attention should be afforded to any indication of fungal infection: whether it be the green lawns of *Penicillium*, black of *Rhizopus*, or red of *Fusarium* species, their occurrence on the surface of the kernel, in the endosperm, or on damaged areas.

When counting the (gushing) "relevant" kernels, an infection rate of as little as 0.5% may require special treatment of the entire lot.

The growth of the rootlets should exhibit uniform development and appear to be fresh. Brown, wilted rootlets indicate loss of moisture due to inappropriate management of the piece. A large proportion of abraded kernels which has caused the rootlets to fall off suggests that the turner is not functioning properly, or that the green malt has been turned too frequently. The loss of the rootlets results in excessive development of the acrospire.

Growth of the rootlets must be inspected daily, and the observation recorded. The same also applies to kernels that fail to germinate.

The development of the acrospire should occur as uniform as possible. Huzzars are undesirable; however, they cannot always be avoided if the lot of barley is not homogeneous, has been frequently sprayed, or has been subjected to abrasion and damage to the rootlets. In contrast to huzzars, which are caused by incorrect management of the piece during germination (warming of the piece, formation of condensation on the surface and subsequent absorption by the kernels, or the development of clumps of green malt whose rootlets are interwoven), these kernels exhibit a dry modification of their endosperms. Damaged kernels experience abnormal acrospire growth; i.e., more huzzars are present.

The modification of the endosperm should produce kernels with a high degree of friability kernel; i.e., they should be dry and flour-like when milled. Kernels that germinate late usually only undergo insufficient modification, while those that are difficult to modify or that have received too little moisture often exhibit a "greasy" texture in the zones along the margin, especially on their ventral sides. Modification should be as extensive as possible in all kernels (homogeneity). Modified endosperm that is waxy or dough-like can result from spraying the piece either too late or too much. Such kernels tend to have off-odors, are difficult to dry, and result in glassy malt which is difficult to convert during mashing.

The moisture content of the green malt should be determined before the piece is transferred to the kiln. Once the maximum moisture content of the piece has been established, efforts are made to prevent losses through evaporation while transferring the green malt. This value is also important for calculating the amount of moisture to be removed during kilning.

Conducting a visual check of the piece at every stage of growth provides information on any corrective measures that may subsequently be needed, even in fully automated systems. The assessment of the finished green malt is also a valuable tool for constant monitoring of the malting process.

1.6 Kilning the Green Malt

1.6.1 The Processes Involved in Kilning

Moist green malt is extremely perishable. Therefore, the moisture must be removed to preserve the malt in a state that allows it to be stored. Kilning brings the biochemical transformations occurring in the grain to a halt and defines the composition of the malt. Another purpose of kilning is to drive out the raw, fruit-like odor and flavor of the green malt, creating the sensory characteristics and color desired for the specific kind of malt being produced. Furthermore, it is necessary to remove the rootlets or culms, as they are bitter and also cause the kilned malt to absorb water.

These goals are achieved by withering and curing the malt. There are two stages in the process of drying the malt:

Withering refers to the removal of water from the green malt at relatively low temperatures, down to a moisture content of approximately 10%.

Drying down to the so-called "hygroscopic point," which occurs at a moisture content of around 18–20%, is not difficult; beyond that, down to 10%, the process begins to slow but is still quite simple to achieve. In high-performance kilns, the "breakthrough" stage is recognizable by the sudden rise in the air-off temperature. In two-decked kilns, slight depressions become visible on the surface of the malt bed, and the culms drop off. Pilsner and Munich malts are withered at different rates.

The *actual drying stage* is referred to as curing in which Pilsner malt is kilned down to a moisture content of 3.5–4%, and Munich malt, down to 1.5–2%. As drying progresses, it becomes increasingly difficult due to the capillary and colloidal forces working against one another. Thus, temperatures of 80–105 °C are required to achieve adequate drying.

The kernel undergoes both physical and chemical changes during the drying process.

1.6.1.1 Physical Changes in the Green Malt
The *physical changes* include the moisture content, volume, weight, and color of the kernel. The reduction in the moisture content from 41–48% down to 1.5–4% must be conducted in such a way that the green malt does not lose an excessive amount of volume. The kernel is turgid due to the moisture it has absorbed. As a result of modification, extremely fine cavities exist in the interior of the green malt, which should be preserved during withering and curing. The malt exhibits an apparent increase in volume of 16–23% – most ideally over 24% – compared to the barley prior to steeping. This objective is only feasible with careful dehydration through the use of high volumes of air and low temperatures. This kind of dehydration is necessary to create malt that will become friable, to retain a strong complement of enzymes, and to present no difficulties during milling. If the grain is dried too rapidly and/or is exposed to excessively high temperatures, it contracts, becoming hard and dense and thus heavy (the hectoliter weight or specific weight should be monitored). In this condition, the malt will not entirely yield the full quantity of extract it contains during the mashing process. Well-modified malts tend to contract less than those that have been poorly modified. The weight of the green malt decreases during drying: 100 kg of barley results in around 160 kg of green malt, which produces approximately 80 kg of kilned malt. The amount of moisture removed from the green malt is therefore equal to the weight of the kilned malt. Half the mass of the green malt consists entirely of moisture. The color changes from that of green malt (2.0–2.5 EBC) to 2.5–4 EBC for Pilsner malt, 5–8 EBC for Vienna malt, and 9.5–21 EBC for Munich malt. Aroma and flavor formation roughly parallels that of color. However, chemical reactions are also involved.

1.6.1.2 Chemical Changes in the Green Malt
The *chemical changes* in green malt effected through kilning arise either through the continued growth of the embryo, as long as it is still alive, or through other reactions after growth has ceased, which endure as enzymatic processes. Finally, after extensive drying and the heat rigor in the kernels has passed, purely chemical reactions influenced by kilning and the moisture content in the kernel will occur. These cause the color of the endosperm to change.

As long as the moisture in the kernel does not fall below 20% and the temperature does not rise above 40 °C, sustained growth can be detected, which is apparent in the lengthening of the acrospire. Enzymatic activity also causes modification to advance. This can be identified by an increase in the quantity of soluble nitrogen and low molecular weight starch degradation products, if at a certain moisture content, a corresponding temperature limit is exceeded, e.g., 23–25 °C at 43%, 26–30 °C at 34%, and 40–50 °C at 24%. It is therefore important to dry Pilsner malt to a low moisture content before this temperature limit is reached.

At temperatures of 40–70 °C, various groups of enzymes function and continue their respective degradation processes until either the declining moisture content halts enzymatic activity or temperatures rise sufficiently to bring about the inactivation of the enzymes. Since the embryo exhibits no further growth, the degradation products are no longer exploited as raw materials for the synthesis of new tissues. Numerous sugars (glucose, fructose, maltose, and sucrose) accumulate in the grain. The free amino nitrogen (FAN) increases steadily and appreciably during withering (12 h at 50 °C), as do all of the amino acids in the upper layers of the malt bed. However, the increase in FAN in the lower layers of the malt bed only lasts about 4 h. By contrast, withering at 65 °C effects an increase in the FAN content in every layer, while losses during curing (80 °C) amount to around 25%. The individual amino acids are influenced differently; for instance, glycine, alanine, and arginine increase significantly during withering, whereas glutamic acid and the amides experience a steady decrease from the very beginning. The aromatic amino acid proline reacts similarly to glycine. The amines, which include histamine, hordenine,

tyramine, and tryptamine, decrease as the temperature rises. Hordenine plays a role in the formation of nitrosamines. If the moisture content is less than 10%, these reactions are also halted, since the enzymes can no longer take part, are inactivated, or are even denatured. The loss of enzymes is more severe if the moisture content of the malt is greater at higher temperatures. Since the enzymes sustain fewer losses in dry heat rather than in moist heat, lightly kilned malt will always contain more enzymes than Munich malt. However, the proportions of enzymes in the respective types of green malts are reversed due to the greater degree of modification in Munich malt.

The starch also changes during the processes of withering and kilning: the gelatinization temperature increases slightly as the withering temperature rises, followed by a decline as the result of an increase in curing intensity from 5 h at 65 °C to 3 h at 90 °C.

Regarding the individual enzymes, β-amylase is damaged to a much greater extent than α-amylase. Nevertheless, due to an increase in the enzyme's activity during withering, α-amylase in the finished malt never drops below the level it had attained in the green malt, even given the losses during kilning. The endopeptidases show an increase in their quantity and efficacy during withering at 50 °C. During the curing stage of kilning, there is no significant damage to these enzymes – even at higher temperatures. The exopeptidases experience a considerable boost in activity during withering. Only the dipeptidases are heavily damaged enough that the quantity in the finished malt is less than that present in the green malt. By contrast, the amino- and carboxypeptidases always exhibit a higher level of activity in kilned malt than in green malt. Endo-β-glucanase is not significantly damaged during the curing process, while exo-β-glucanase is inactivated in ever greater quantities as the temperature rises above 50 °C. In Pilsner malt, a loss of two-thirds of the initial value occurs during kilning. The polyphenol oxidases and peroxidases are very sensitive to higher temperatures and are palpably inactivated during the kilning process at temperatures above 80 °C, an occurrence that leads to higher anthocyanogen values in the wort and beer.

Damage to the catalases increases over the course of withering. Once curing begins at 80 °C, catalase activity is no longer detectable. The lipoxygenases are quite functional from the beginning of withering, but their activity reaches a maximum at 60 °C. Some residual activity occurs during curing at 80 °C; however, this rapidly decreases at 90 °C.

The *chemical changes* at higher temperatures are evident in the nitrogen fractions. Depending on the moisture content and temperature, the dispersity undergoes a shift. High molecular weight degradation products coalesce to form larger particles. This leads to a part of this fraction becoming insoluble. Even if this shift is less perceptible in Pilsner malt than in Munich malt, it nevertheless plays a role in the flavor, capacity for foam formation, and the stability of the beer. Pilsner malt must therefore be cured at a minimum of 80 °C, while Munich malt exhibits a shift in dispersity to larger particles within the range of 100–105 °C. Most conspicuous are the chemical changes that cause an increase in the color of the endosperm and the distinct, pleasant roasted aroma that is characteristic of Munich malt.

These reactions involving *color and aroma formation* occur at temperatures above 100 °C and at a moisture content of around 5%. The reactants present in the green malt are the sugars and protein degradation products, such as amino acids as well as di- and tripeptides. The amino groups on the amino acids and the peptides react with the carbonyl groups on a sugar to form an N-substituted glycosylamine. Then, as a second step, these react by means of a Schiff base to an N-substituted ketosamine, which is in equilibrium with its enol form. Up to this point the reactions are reversible and the products do not exhibit color. From here, two reaction sequences, beginning with either the enol or keto form, are possible. An important intermediate product of the first pathway is 3-deoxy-D-glucosone, which can, firstly, continue to react by itself or via intermediate compounds with carbonyl groups to form melanoidins (type A); secondly, it can form hydroxymethylfurfural via a dehydration reaction. This aldehyde is extremely reactive and, in turn, condenses with amino acids to form melanoidins (type B). The reaction with the keto form of the ketosamine mentioned above takes place via an unsaturated hexosone, which can also condense with amino acids to form melanoidins (type A). In addition, a number of reactive low molecular weight degradation products with carbonyl groups are generated, e.g., aldehydes from the Strecker degradation of amino acids. The carbon structure of these aldehydes is one carbon atom smaller than that of the original amino acid due to the elimination of carbon dioxide and ammonia from the molecule. Strecker aldehydes, which each develop a characteristic aroma, are very reactive. They undergo condensation reactions with other aldehydes, the degradation products of sugars,

furfural, other dehydration products, or aldimines and ketimines to form brown pigments. In the formation of melanoidins, intermediate products are formed via various pathways, which can be categorized as reductones.

The antioxidative effect is dependent not only on the reactants (amino acids, peptides, and sugars) but also on the molecular weight of the Maillard products. While those below 1 kDa exhibit only a minute antioxidative effect, there is a peak at 5 kDa. Since the higher molecular weight melanoidins are only formed under greater thermal stress (temperature and time), there is a significant correlation between color, aroma, and the antioxidative effect. However, under certain conditions, such as concentration and presence of oxygen or metal ions, a number of these antioxidants can also become pro-oxidants and thus promote oxidation reactions. In addition, some products are first generated over the course of the Maillard reactions, which possess both antioxidative and pro-oxidative properties. This is especially true for early products of the Maillard reactions prior to the Amadori rearrangement, which give rise to free radicals.

Amino acids exhibit a higher reactivity the farther the carboxyl and amino groups are from one another on the molecule. They each impart distinctive aromas and/or flavors to the malt. For instance, glycine develops a strong color but has a weak aroma, while alanine exhibits a weak color but possesses a flavor similar to glycine. In contrast, valine reacts slowly and forms brownish-colored melanoidins with a pleasant aroma. Leucine due to its larger size also reacts more slowly and has only a weak color but has a distinct, bread-like, roasted aroma. In order to bring about these reactions with amino acids, curing temperatures of 100–105 °C must be maintained for 5–6 h in the production of Munich malt.

However, it is also necessary that the low molecular weight compounds formed as a result of starch and protein degradation are present in sufficient quantities. This is one of the reasons why green malt destined to become Munich malt is more highly modified and is maintained at a higher moisture content for longer periods within a temperature range of 40–60 °C during the withering process. With some kinds of barley, it is nevertheless difficult to produce these degradation products in the desired quantities. The natural capacity of barley and green malt to create these compounds is a prerequisite. In particular, barley with a very low protein content is less suitable for the production of Munich malt.

The formation of the desired color and aroma compounds will not occur by simply heating the green malt. Under certain circumstances, burnt-smelling and bitter-tasting substances ("assamars") may form, which affect the aroma and flavor of the beer.

Temperature control and the rapidity of this process have a major influence on the aroma profile of the finished malt. The formation of precursor substances is the reason the speed of the reactions is important, and as these occur, enzymatic activity is first fostered temporarily and then subsequently undermined. Lower initial temperatures during withering (35–50 °C) result not only in a higher extract content but also in a higher value obtained using the VZ 45 °C mash method. The TBI is also more favorable with gentle drying, meaning that the value is lower. This also parallels the formation of Strecker aldehydes and 2-furfural. Forced drying, such as a constant withering temperature of 65 °C, results in the formation of more color and aroma substances. At higher temperatures during withering, the formation of lipid degradation products, such as hexanal and heptanal, among others, is either diminished, or the substances are more rapidly driven out of the grain. The highest values for lipid degradation products and, concurrently, the lowest levels of Strecker aldehydes are attained by prolonged withering (20 h at 50 °C with fans operating at 50% capacity), as is carried out in germination/kiln vessels. Over this duration, the highest amounts of unsaturated carbonyls are also formed.

By increasing the curing temperature, the Strecker aldehydes, 2-furfural, some furans, and alcohols increase exponentially in a withering process identical to one employed for Pilsner malt. The substances originating from lipid metabolism do not react in a uniform manner. Pentanal, octanal, (*E*,*E*)-2,4-octadienal, and certain ketones (2-pentanone, 2-hexanone, 2-heptanone, and 2-decanone) continue to increase at and above a curing temperature of 85 °C. The majority of the other aroma compounds generated by lipid metabolism such as γ-nonalactone are driven out of the malt at higher curing temperatures.

Sugars form heterocyclic compounds at high curing temperatures. Through intermolecular rearrangements, through enolization, a sugar is transformed into an endiol as an intermediate product. A molecule of water is cleaved from this, and the resulting dicarbonyl compound becomes a reactant with amino acids. If a sulfurous amino acid, e.g., cysteine, reacts with the dicarbonyl compound, 2-acetylthiazole is formed after a number

of intermediate steps. The formation of pyrazines (from two aminoketones) or oxazoles (synthesized from aminoketones and organic acids) also advances parallel to the first steps in the Maillard reactions. Pyrroles are created from dicarbonyls and 1-amino-1-deoxy ketoses. Proline reacts with reducing sugars to form pyrroles, acylpyrrolidines, 1-acetylpyridine, and maltoxazine, as it is known, among others.

Oxygen heterocycles, such as pyran-4-one, maltol, isomaltol, and furaneol, do not possess a nitrogen atom. Many of these substances exhibit intense aromas and flavors, with notes ranging from bread, potato, and popcorn to mushroom-like. For instance, some of the proline derivatives also have a bitter flavor.

The composition of the heterocycles as well as the position and number of methyl groups on their carbon rings determine the aroma as well as their sensory threshold values. These can range from 10,000 to 0.002 ppb.

These substances are not always pleasant. In the case of Munich malt, the products of the Maillard reactions, including the heterocycles, are desirable. At higher temperatures or due to excessive thermal stress prior to or following the wort boiling process (refer to Section 2.5.5.4), Maillard products can also produce substances in the finished beer that are perceived as off-flavors.

With an increase in the curing temperature from 70 to 85 °C, the N-heterocycles increase significantly, especially the pyrazines and 2-acetylpyrrole. Raising the temperature from 85 to 100 °C brings about an additional increase of 60–300% in the N-heterocycle content. This can be further elevated by employing a withering process for Munich malt and curing at 100 °C; a larger quantity of amino acids and sugars are present as a result of the "hot withering" procedure.

The quantity of invert sugar and amino acids as well as smaller peptides decreases during kilning due to melanoidin formation. Since melanoidins are somewhat acidic, the pH of the laboratory extract or the Congress wort drops with higher curing temperatures. The effect of the phosphatases, which cleave inorganic phosphate off of organic phosphorus compounds, also contributes to the acidity. Furthermore, secondary and tertiary phosphates are precipitated at higher curing temperatures, which is evident in the reduced buffering capacity of the malt.

Organic sulfurous compounds are also transformed during kilning. The *S*-methyl methionine (SMM) formed during germination degrades in the heat generated during the kilning process. Dimethyl sulfide (DMS) is cleaved from the molecule. However, DMS is very vulnerable to oxidation and can form dimethyl sulfoxide (DMSO) in the presence of oxygen. DMSO, which has a high boiling point, can be converted to DMS through substantial thermal stress as well as by yeast and certain bacteria.

Dimethyl sulfide: withering processes at higher temperatures initially drive out more *S*-methyl methionine from the green malt, and yet withering at lower initial temperatures produces malt with the lowest values. In addition, more dimethyl sulfoxide, which is not as volatile, is formed from DMS at higher withering temperatures. The amount of DMSO rises even more at high curing temperatures. All malt contains DMSO in addition to DMS-P and free DMS. Malt that has been cured at higher temperatures consequently possesses less DMS-P and DMS but more DMSO. At a normal curing temperature of, e.g., 80 °C, malt contains 11 ppm DMS-P and 20 ppm DMSO, whereas at 90 °C, only 6 ppm DMS-P but 30 ppm DMSO. While DMS-P cannot be metabolized by brewer's yeast, some yeast strains are capable of reducing small amounts of DMSO to DMS using the corresponding reductase. The increase during fermentation and maturation is only 5–10 ppb, if any. However, wild yeasts and some types of bacteria possess DMSO reductase and are thus capable of releasing considerable amounts of DMS into the beer, rendering it undrinkable.

The malt produced using newer barley varieties brings high concentrations of DMS-P into the curing process. The DMS-P content can be reduced by curing at high temperatures (see above), but this is inevitably accompanied by the formation of more color and aroma compounds. An Arrhenius plot illustrates that a value for TBI of 13 and a DMS-P content of 7 ppm can be achieved after curing for 5.5 h at 84 °C. The same values are obtained in 3 h at 90 °C. There is an "operating window," according to which the duration and temperatures can be referenced to achieve certain specifications for DMS-P and the TBI. However, this must be empirically determined for every kiln. Factors include the height of the malt bed, the fan speed, and, therefore, the change in temperature over time in the individual layers of the malt.

As a rule, the upper limit for DMS precursor in Pilsner malt is 5–7 ppm.

For Pilsner malt (color <3.5 EBC), a curing temperature of 83 °C is usually sufficient to avoid an excessive rise in the TBI (greater than 14 in the Congress wort, refer to Section 1.8.3.12).

Withering at high temperatures or a high level of thermal stress during withering has a negative effect on the quality of the malt and beer. This shortcoming can be countered by withering at constantly rising temperatures, from 50 to 70 °C (1.7 °C/h) within 12 h. The resultant beers, both fresh and aged, performed best when tested as part of sensory evaluation.

Sensory evaluation of fresh and aged beer determined that curing temperatures between 80 and 88 °C produced an equally satisfactory result. Naturally, with higher curing temperatures, a more pronounced malty flavor will be present in the beer. For instance, the effects of higher amounts of Strecker aldehydes and lower values for lipid degradation products at higher curing temperatures seem to balance each other out. The increase in Strecker aldehydes only has a negative effect on Pilsner malt above 88 °C.

Malt cured at 90–100 °C contains less DMS precursor than does malt cured at lower temperatures. Nonetheless, the amount of DMS precursor and thus the formation of free DMS during fermentation are dependent on the intensity of the kilning and wort boiling processes. Other factors play a role as well: the barley variety, the climatic conditions during cultivation, the germination parameters, and the degree of protein modification attained during malting.

The polyphenol content is somewhat diminished by the action of the oxidases during withering. As the curing temperature increases, peroxidases and polyphenol oxidases are progressively inactivated, to such an extent that the Congress wort produced using this malt will have a higher polyphenol content, particularly higher anthocyanogen values. This lowers the polymerization index. The tannoid content increases (refer to Section 1.1.2.6). In this way, polyphenols can form compounds that impart color, and this is also possible through reactions with Maillard products.

The upper limit for the curing temperature is between 80 and 85 °C for the production of Pilsner malt. Above these temperatures, the increase in color during the downstream brewing process becomes too intense for pale beers.

Given their prevalence, triglycerides serve as a representative example of lipid degradation. They are cleaved into long-chain saturated and unsaturated fatty acids by the lipases at two different temperature optima during withering in addition to their degradation during germination. Oxidation by lipoxygenases occurs predominantly at low withering temperatures to produce hydroperoxides; finally, through auto-oxidation, they form carbonyls, ketones, alcohols, lactones, and furans, which all evince strong aromas. These volatile substances contribute to the aromas and flavors in beer, especially in the aging process. For instance, the aldehydes formed during withering as lipid degradation products at low temperatures, such as hexanal and (*E*,*E*)-2,4-decadienal, are not prevalent in malt withered at higher temperatures (65 °C). Likewise, the higher the curing temperatures are (e.g., 88–90 °C), the lower the concentrations of these aldehydes.

Phosphates and oxalates decline appreciably with increasing curing temperatures in barley malt, while they hardly change in wheat malt.

The denaturation or inactivation of some of the enzymes during kilning means that the extract yield will also be influenced: the higher the temperature, the longer the duration of kilning, and the higher the initial moisture content, the lower the extract yield will be. Freshly cured malt supplies less extract than malt that has been stored. This is due to the colloids having had their "hydration shell" partially removed during kilning, which incidentally also causes the runoff from Congress wort to be opalescent. Over the course of storage, the malt absorbs a slight amount of moisture, and the colloids that are dehydrated again expand as they absorb moisture. The greater inactivation of α-amylase, and especially of β-amylase, at higher curing temperatures also results in a drop in the limit of attenuation of the Congress wort.

In kilns direct-fired using sulfurous fuels (e.g., coke), the color of the malt is lighter. This is due less to the bleaching effect of the sulfur dioxide and more to blockage of the reactivity of functional groups on certain molecules, especially of those on aldehydes, sugars, and their reaction products.

Heating oil with a higher sulfur content can lead to "striping" of the malt and to black spots on the husks, which are negligible but may still result in the maltster receiving complaints. Heating oil with a low sulfur content (below 0.5%) is recommended. Specially designed furnaces even allow the combustion of fuel oil that is richer in sulfur. However, the pH of the malt can drop so much that it becomes difficult to process in the brewery.

Withering and curing in direct-fired kilns bring about the formation of nitrosamines in the malt, which survive the brewing process and can be found in the finished beer. Their precursors are the amines (dimethylamine, ethylamine, tyramine, hordenine, and gramine, among others) formed during germination and nitrogen oxides that result at higher flame temperatures. These are collectively referred to as NO_x but mainly consist of

NO and NO_2, with the latter being the primary perpetrator in the nitrosation of amines during withering. The nitroso compounds are then split into nitrosodimethylamine (NDMA, belonging to a group of compounds simply referred to as "nitrosamines"). The sulfur content of the fuel blocks the nitrosation reaction, which results in a substantial decline in NDMA formation. The so-called "low NO_x furnaces," which increase the ratio of combustion air to fuel gas to approximately 1.8 : 1, also achieve a reduction. Unfortunately, this does not always reduce the concentration adequately to below the upper limit of 2.5 ppb. Using indirect heating systems provides the best solution, as they have been specifically designed to resolve this issue.

The suspicion that direct-fired kilns foster the formation of *polycyclic, aromatic hydrocarbons* (PAHs) could not be confirmed in research monitoring 3,4-benzopyrene. Rather, it seems more likely that environmental conditions play a more important role in shaping the PAH content of a malt.

When foods are heated, other toxic substances are generated, such as chloropropanols, acrylamides, and furans. They can be derived from simple precursors, such as amino acids, lipids, and sugars, which are already present in brewery raw materials or in the resultant intermediate products. Even if these toxins do not accumulate in the food web, they are known to be carcinogens in animals. They could also pose an as-yet-unquantified threat to human health.

Chloropropanol or its widespread derivative 3-chloropropane-1,2-diol (3-MCPD) can, for instance, arise at higher kilning temperatures or in roasting processes. However, since the proportion of specialty malts in most beers is very low, this substance and the esters derived from it have yet to be detected in beer.

Acrylamides are also created when malt is heated, however, at lower temperatures than 3-MCPD. Degradation of the acrylamides begins once again at temperatures above 170 °C (roasted malt). Research has shown that light beers (color below 10 EBC) had the lowest levels. The mean value was 2.4 ppb, while the maximum was 11.2 ppb. No correlation with beer color was discovered. The malt generally plays a role in this case, as does the brewing process. The content increased by 30% in the brewing process and then was followed by a decrease of 50%.

Furan is a volatile compound with a strong flavor. Nonetheless, over the course of brewhouse operations, e.g., boiling, it is driven out of the wort. The maximum concentrations found in beer are less than 20 ppb.

Malt dried in direct-fired kilns powered with liquefied petroleum gas or natural gas has a s*ulfur dioxide* content of 1.5–8 ppm; with light fuel oil (sulfur content: 0.2–0.5%), this rises to 5–10 ppm, and with coke (sulfur content: approximately 0.9%), it reaches 20–33 ppm. Careful studies have shown that the SO_2 content of malt has no impact on the SO_2 content of beer. The sulfur content of the fuel oil results in a very substantial reduction in nitrosamines, and countermeasures, such as increasing the ratio of gas to combustion air to 1 : 1.8 (e.g., in gas-fired kilns), have been successful.

1.6.2 Kilns

Malt kilns are used to dehydrate and cure green malt. The various kinds of kilns are heated either indirectly or directly with hot air or through a combination of heat-generation methods. The essence of kiln design ultimately amounts to the arrangement of the decks and the height of the grain bed: horizontal or planar kilns with one, two, or three decks and vertical kilns (older ones for batch operation or modern ones for continuous operation). Modern kilns are mostly of the high-performance variety with one or two decks, one above the other or next to one another. Kilns with three decks next to one another (Triflex kiln) also exist. Moreover, there are combination systems, for instance the various types of germination boxes that also serve as kilns. Kilns are also categorized by the type of heating. There are those that use indirect heating, where the drying air is warmed in a heating system, and direct heating, where the combustion gases pass directly through the green malt.

Concern regarding the formation of nitrosodimethylamine (NDMA, refer to Section 1.6.1.2) has prompted the conversion of most direct-fired kilns to those that indirectly heat the air used to dry the malt. This has been achieved by retrofitting them with new heating systems. All kilns built after 1980 are fitted with an indirect heating system. These can be further subdivided according to the type of heat transfer medium they employ (steam or hot water). With indirectly heated kilns, the type of heat transfer medium is less important. However, in the event of a leak in the system, one should strive for the same degree of purity in the heat transfer medium as in direct-fired kilns. In addition to avoiding contamination of the malt with harmful impurities, the objective of minimizing environmental pollution also plays a significant role.

1.6.2.1 Single-deck High-performance Kilns
Single-deck high-performance kilns are the most prevalent kind of kiln design. They are characterized by a high grain bed depth of 0.6–1 m and high specific deck loading, at 250–400 kg/m^2 (green malt) and 200–320 kg/m^2 (finished malt). Both the withering and drying processes are carried out on a single deck, which is not equipped with a turning device. The kiln consists of the following elements: the *deck*, made of particularly strong profile wire, a type of wire that is resistant to lateral deformation and that has a significant free area (30–40%) to permit the free flow of air. In order to achieve a smooth, even surface, the individual sections of the deck fit firmly next to one another and are arranged on a support grid made of steel grate, which, in turn, is attached to the profile iron. The kiln deck is anchored in the wall in such a way that it allows for a certain amount of expansion and contraction as the temperature rises and falls. In most cases, either one or two sections of the deck are designed to tilt to facilitate unloading. If the deck only tilts at one point, the kilning chamber has to be built to the required height to permit the deck to tilt up. The chute through which the malt is cast from the kiln would then be located on the kiln wall. If two segments of the deck tilt, this requires the outlet to be in the middle of the chamber. Occasionally, a gangway is installed around the kiln deck.

Ventilation of the kiln is implemented using a fan of a suitable size, which is located at the level of the stoking chamber or the heating coils. The fan draws the air from either the fresh air shaft or the recirculated air duct and forces it into the hot air chamber above. The air then moves through the bed, permeating the grain on the kiln deck. The air coming off of the malt bed subsequently rises into the chimney, which forms a common shaft with the recirculated air duct. There, the air can either be recirculated through the kiln or released as exhaust by channeling it in the appropriate direction using a tightly shutting flue damper flap or diaphragm.

The *stoking chamber* is designed to be free of any drafts. With indirectly heated kilns, a heating system (thermoblock and calorifiers for steam or hot water) is employed instead of a furnace. The instruments for monitoring kiln operations are usually installed in the stoking chamber if the kiln is not controlled from a central control room.

The *hot air chamber* is intended to allow the volume of air forced into the space under the kiln deck by the fan to become evenly distributed under the malt. The height of the chamber depends on the area of the kiln deck and any fixtures or equipment, which generally include the chute for casting the malt onto the tipping deck and the conveyor for the kilned malt. The lower the height of the hot air chamber and the more fixtures and equipment there are in that space, the more difficult it is to evenly distribute the air and thus maintain a uniform temperature in the grain bed. A diffuser panel is located between the aperture where the hot air is blown in from the fan and the kiln deck. This panel keeps the direct stream of hot air from striking the grain bed at full force and also prevents malt culms from falling into the aperture. A grating or a perforated sheet metal baffle at the hot air inlet has proven effective in distributing the air more evenly.

The *fan*, usually set inside a housing, has to generate pressures of 60–200 mmAq, depending on the height of the grain bed, in order to supply the quantities of air sufficient for drying the grain. Heating coils, calorifiers, etc. also cause additional losses in pressure. The fans are designed to perform at a high output. These fans propel 2500–3000 m^3 of air per kWh through the grain bed for the duration of the kilning process (20 h). In the case of Pilsner malt, a volumetric airflow of 4000–4800 (up to 5000) m^3/(t·h) is required, which is then reduced to 2300–2700 m^3/(t·h) during curing. This can be carried out by partially closing the fresh air or the exhaust air damper. The rotational speed of the fan can also be reduced by means of a variable resistor, a repulsion motor, or, in more modern fans, a frequency controller. The air required by the kiln fluctuates during winter and summer operations and can be adjusted using different sizes of V-belt pulleys. Depending on the rhythm of kilning operations, a longer duration for both withering and curing is feasible in more modern kilns. A slightly heavier load of 500 kg or more of green malt can be processed, given that the cycle is complete in 30–32 h. To achieve this, the fan speed would need to be increased to allow a volumetric airflow of 3200 m^3/(t·h).

Of the various heating systems employed for kilning, only those that indirectly heat the malt will be discussed in this edition. Systems for direct-fired kilns can be described in earlier editions of this book. Currently, modern devices for heat generation in malting facilities are predominantly powered using industrial fuels, such as fuel oil, natural gas, and liquid petroleum gas.

Among liquid fuels, extra light fuel oil (EL) is predominantly utilized according to DIN 51603. It can be ignited in vaporizing or atomizing oil burners with no preheating. The net calorific value (NCV, the heat of condensation of the water vapor contained in the exhaust gases is excluded) is 42,700 kJ (10,200 kcal), while the gross calorific value (GCV)

accounts for the heat of condensation of the water vapor in the exhaust. For EL fuel oil, the GCV is 45,400 kJ (10,845 kcal).

The most frequently employed gaseous fuels vary in quality: natural gas L has an NCV/GCV of 8.8/9.8 kWh/m^3 gas, while those of natural gas H is 11.1/14.0 kWh/m^3 gas. Liquefied petroleum gas has an NCV/GCV of 34.4/37.4 kWh/m^3 gas or 45,800/49,800 kJ/kg (10,940/11,900 kcal/kg). Natural gas and liquefied petroleum gas are very pure. Nonetheless, the gas delivered by the supply grid was piped over longer distances and previously contained a number of by-products. These included impurities such as tar, benzene, ammonia, and sulfur, all of which had to be removed through careful treatment.

In the case of indirect heating, combustion of the fuels described above occurs in appropriately dimensioned furnaces with large heat-exchange surfaces, where the air is heated before it reaches the fan. The temperature in the furnace is approximately 750 °C. The exhaust from the combustion of the fuel (flue gas) is then fed into the so-called profile cassette units where the heat from the flue gas is transferred to the air that flows through in a direction perpendicular and countercurrent to the flue gas. The stainless steel heating surface is so large that the flue gases are cooled down to below 50 °C during withering, causing the water contained in the fuel to condense. The heat liberated through condensation is also exploited to warm the process air. This, in turn, increases fuel utilization, so that when the calorific value of the fuel is calculated, the GCV is closer to the true value. It is, therefore, possible to achieve or even to surpass the efficiency of the kilns that were formerly direct-fired with gas because the water present in the gas somewhat increases the moisture in the air used to dry the malt. This effect would have been particularly significant, given the lower moisture content of the withered malt at the end of the drying process.

Heating systems, through which *steam* or *hot water* (approximately 110 °C for withering and 160 °C for kilning) flows, are simpler. Exhaust steam at 1.5–2 bar (overpressure) can also be reutilized in the withering stage. However, higher steam pressures are required for curing.

Though their designs vary, single-deck kilns have proven themselves effective. They are not difficult to operate, and the kilning process can be fully automated. Kilning takes 18–21 h for both Pilsner and Munich malts.

The electrical energy required to power the process largely depends on the height of the grain bed. Direct-fired kilns require less energy (25–40 kWh of finished malt) than those heated indirectly (33–48 kWh/t of finished malt). The amount of heat energy usage diverges along similar lines: with direct-fired kilns or the low-temperature flue gas furnaces mentioned above, the heat energy usage amounts to $3.35–4.40 \times 10^6$ kJ/t or $0.8–1.05 \times 10^6$ kcal/t of finished malt, whereas the energy consumption for kilns indirectly heated with hot water or steam (due to losses in the boiler) amounts to $4.0–4.6 \times 10^6$ kJ/t or $0.95–1.1 \times 10^6$ kcal/t of finished malt.

1.6.2.2 Two-deck High-performance Kilns A desire to better utilize the heated air exiting the top of the bed of curing malt, that is to utilize it directly for the withering process, prompted the reintroduction of multi-deck kilns, as described in Section 1.6.2.6 but with significantly higher rates of kiln deck loading. The decks can now be arranged one above the other or next to one another. The latter involve reversal of the airflow in the kiln (see below). For the entire withering and curing period, the grain remains on the same deck. However, in high-performance kilns with one deck above the other, the malt must be transferred from the upper to the lower deck at the end of the withering process.

Two-deck kilns with their decks arranged one above the other are predominantly round. The deck can either be rotated with a fixed mechanism for loading/unloading or is stationary with a rotating loading/unloading screw auger. The specific deck loading is 350 kg finished malt/m^2 (435 kg barley as green malt). The rotating deck is turned via a peripheral gear ring run by drive motors. The air is directed through the kiln as follows: one type of kiln is designed to pull the air in through the fresh air duct over a crossflow heat exchanger (refer to Section 1.6.5.2). In a second type of kiln, the air is pulled over a large heat-exchange surface (furnace) by a fan mounted between the decks. The air passes through the curing deck and then – if necessary, with the addition of slightly preheated fresh air (crossflow heat exchanger) – is forced through the withering deck. The withering and curing processes are each planned to last 20 h, and therefore, the fan must provide an output of 3200 m^3/(t·h), although a reduction by approximately 50% through the use of a frequency controller is desirable. The heat energy required is $2.1–2.3 \times 10^6$ kJ/t (or $0.5–0.55 \times 10^6$ kcal/t), facilitated in part by the crossflow heat exchanger. The electrical energy required is 45–50 kWh/t of finished malt.

Another type of kiln design employs two blower fans: the first fan pushes the heated air through the curing deck (output ≤ 3000 m^3/(t·h)). The second fan moves this air from the space above the lower deck and forces it – blended with the preheated fresh air and adjusted via a second heat exchanger to the withering temperature – further up through the withering deck (output ≤ 3800 m^3/(t·h)). Both fans are regulated by stepless variable speed controllers.

The kilns are loaded with green malt using a mechanical conveyor. The green malt is evenly spread out on the deck by a vertically adjustable horizontal screw auger. This device is also utilized to transfer the withered malt onto the lower deck. An identical auger performs the same function on the curing deck.

The *two-deck kilns with square or rectangular decks situated next to one another* have become known in German as *Luftumkehrdarren* (parallel two-deck kilns with a variable airflow system). Once the kilning process is complete, the deck previously serving as the curing deck is loaded with green malt and becomes the withering deck. Likewise, the previous withering deck now becomes the curing deck. The air warmed by the crossflow heat exchanger is further heated indirectly by a kiln air heater and forced through the deck. The fan capacity in these kilns is designed to be lower than that in the kilns described above, since the grain does not move during the processes of withering and curing. Consequently, the stratified layers of grain are not disturbed (1500 m^3/(t·h)). The air coming off of the malt bed is now led downward into the air-off shaft and taken in by the larger capacity withering fan (2500 m^3/(t·h)). In order to provide the larger amount of air required for the withering process, preheated fresh air (refer to Section 1.6.5.2) is added. Both streams of air, each with different qualities, are now brought to the desired withering temperature in an additional heat exchanger. Both fans are regulated by a computer-controlled variable speed frequency converter, the output of which is determined by the moisture content of the green malt, the progress of both withering and curing, and the type of malt being produced. The consumption of heat energy is 2.1–2.3 × 10^6 kJ/t (0.5–0.55 kcal/t) finished malt, and the electrical energy required is 30–35 kWh/t. The specific kiln deck loading is between 330 and 400 kg/m^2 of finished malt.

The decks are loaded and unloaded by a screw auger that is capable of being raised and lowered as well as moved back and forth at an adjustable speed over the kiln deck. The green malt is fed either with a swing pipe or a swiveling screw conveyor. Stripping the malt from the kiln is carried out by a screw or trough chain conveyor situated either lengthwise or at an angle to the direction of movement.

The idea of employing the unsaturated air drawn off of one kiln to wither the green malt in a second kiln led to the "Triflex kiln" design. Three identical single-deck kilns, each with its own fan and separate heating system, are connected to exhaust air and recirculated air ducts. The unsaturated air from curing malt in one kiln flows into the recirculated air duct, which leads to the next kiln where green malt is undergoing withering. Two of the decks are always concurrently loaded with green malt; one deck receives 45% of the green malt, and the other 55%. Kiln A is loaded first with 409 kg of green malt, while the lesser amount weighs 327 kg when cured. This kiln is operated on a 20 h cycle with a fan designed for an output of 3500 m^3/(t·h). Kiln B is loaded second with 500 kg of green malt or when cured 400 kg/m^2 for withering and curing over a duration of 32–33 h. After 14 h, breakthrough is reached in kiln A, and the airflow through the bed is reduced to two-thirds of its original volume. The air coming off the bed is mixed with fresh air and heated to the withering temperature. Meanwhile, breakthrough has also been achieved in kiln B, so the air coming off of it is routed to kiln C (45%), which has been newly loaded with green malt. Part of this air stream is diverted to kiln A, which is again loaded with green malt, to begin the withering process anew. This method of kilning is also extremely economical, since only completely saturated air exits the kiln. The heat energy consumption of a Triflex kiln is just under 2.1 × 10^6 kJ/t (or 0.5 × 10^6 kcal/t), while the electrical energy requirement is 26 kWh/t finished malt.

1.6.2.3 Combination Germination and Kilning Units *Combination germination and kilning units*: a number of these box systems developed over the past decade have proven successful. Two basic designs are discussed in detail below.

The principle of the germination and kilning box system essentially corresponds to that of a *rectangular germination box*. However, the system is designed to facilitate the movement of large volumes of air through amply dimensioned air ducts. The space under the germination box deck is 2.9–3.2 m in height. The specific deck loading is 500–630 kg/m^2 for a total capacity of 130–170 t. The building is made of prefabricated concrete elements. Despite the insulating properties of

the structural material, temperature fluctuations are unavoidable, making flexible seals necessary. Aerated concrete provides insulation between the boxes. The deck is constructed of zinc-plated, slotted metal sheets, which have already proven to be well suited for this purpose. A wedge-wire deck is also a practical option.

A Saladin-type helical turning device is commonly utilized during germination but not during kilning. However, it is also employed to discharge the finished malt after kilning. The vertical augers on the turning device are locked in place during the transfer process, so as not to damage the malt. Since the kilned malt is looser than the green malt, the turning device cannot exert enough force to discharge it from the kiln. Therefore, a folding shovel – usually constructed in three pieces – is attached to the turning device to aid in the removal of kilned malt.

A more recent design employs a transverse auger that is situated just above the kiln deck. The Saladin-type turning device moves the cured malt without compression, gently pushing it toward the transverse auger. Almost all of the culms remain intact and attached to the kernels, thus minimizing the numbers that fall into the space below the deck. The grain is fed into a horizontal conveyor (auger, Redler drag chain conveyor, and conveyor belt) that runs along the longer side of the box. The length of time it takes to discharge the finished malt is equivalent to the time required for the turning device to move from one end of the box to the other.

The ventilation system for germination is installed at the front end of the box. Each of the three to six germination and kilning boxes in a system possesses its own fan (600 m^3 air/(t·h)), its own air ducts, and corresponding refrigeration unit. The ventilation and heating system for the kiln is located at the opposite end of the box. This system is – depending on the duration of withering and curing – capable of supplying four to six boxes. For reasons of fan capacity and energy expenditure, the higher deck loading compared to individual single-deck kilns requires that the withering period be longer. Normally, withering and curing are estimated to last 33 h. This necessitates having one heating system installed for every four germination and kilning boxes. The fans are generally not enclosed with an output of 2500 m^3/(t·h); the energy expenditure is only about 40 kWh/t despite the high bulk loading density. The average heat energy requirement is 3.8×10^6 kJ/t (0.9 million kcal/t) of malt. The kiln air is channeled precisely, just as in single-deck kilns. There is a fresh air shaft, a recirculated air duct, and exhaust air vents, which are usually located on the opposite side from the air inlet. The air, previously heated directly with gas, is now heated indirectly in modern kilns using furnaces suitable for this purpose (refer to Section 1.6.2.1). The distribution of the heated air to the respective boxes containing the malt to be dried occurs over a central shaft on the "kiln side" of the system through heavily insulated gates or ports that can be sealed tightly.

Curtailing kilning to approximately 28 h for the purpose of more effectively utilizing the germination period usually requires an acceleration of the withering phase by altering the air throughput and temperature. The volumetric output of the fan is increased to approximately 3000 m^3/(t·h), which results in higher electrical energy consumption. Further curtailment of the withering and curing processes – which is necessary when adding more germination and kilning boxes (up to six) – compels the maltster to kiln malt on a daily basis in order to maintain the requisite 24 h cycle. In such cases, the fans must provide an estimated volumetric output of 3300–3700 m^3/(t·h) during the withering process. Efforts to save energy have led to coupling two germination kilning boxes in which the air coming off of one of the boxes after "breakthrough" is further utilized to heat the air needed for withering the malt in the other box. This requires an air recirculation system and a second group of fans as well as an additional heating system to heat the blend of fresh air and recirculated air for the withering process. The total time necessary for withering and curing amounts to 2×24 to 28 h, depending on the individual cycles.

The germination and kilning boxes described above are fed by a conventional steeping system or by means of a grain-cleaning auger. Another type of germination and kilning system with a capacity of 300 t per unit operates according to a different principle: these boxes measure 630 m^2 and are loaded "dry" over a period of 5 h with barley using a Redler drag chain conveyor. The grain bed is leveled and then sprayed to rapidly increase the moisture content using nozzles mounted on a turning device. The grain bed is turned slowly with the turning device only advancing at a rate of only 0.2 m/min, while the augers mix the steep liquor and the barley at a high rotational speed (42 rpm). The steep liquor is supplied by means of a channel running along the wall of the unit. The turning device moves more rapidly across the grain bed with subsequent sprayings. The augers on the turning device, however, are set to rotate more slowly as the grain germinates. The moisture

content of the grain is boosted very effectively, as indicated by the low total steep liquor consumption of 0.9 m^3/t. This volume per metric ton is only 30–40% above the theoretical requirement. The ventilation system for the germinating grain (five fans with a total capacity of 600 m^3/(t·h)) ensures that the air is distributed evenly over the entire length of the box. Likewise, six fans with a total volumetric capacity of 3800 m^3/(t·h) malt are installed in a machine room that serves two germination and kilning boxes. The air is heated by six gas-fired heaters. The malt is cleared from the kiln in 5–6 h using a device similar to the "Koch" system, which conveys the kilned malt by means of a transverse screw conveyor to a Redler drag chain conveyor. The time required for production in these large units is 2 days for steeping, five and a half to six days for germination, and one and a half days for kilning. Unloading the finished malt and subsequently reloading the unit take one complete workday.

Round germination and kilning boxes (refer to Section 1.5.3.3) were designed as single or multi-level units. However, for the sake of energy recovery and also to lower energy costs, they are now only constructed as two discrete units, a germination box and a kiln (mostly round in cross section), designed in a two-deck arrangement. Interestingly, the curing air in these germination and kilning boxes was directed to the space under the corresponding deck via a central shaft through a series of insulated, tightly sealable flaps. The air ducts are very short, for example, around 8 m in the units for 200 t of barley (as green malt). The curing air is recirculated through its own dedicated duct. An additional duct channels the moisture-laden air coming off of the withering malt to the barley freshly cast out from the steep, which serves the purpose of warming it up.

The single-level *Unimälzer* is based on a similar principle, but it also receives the curing air from the peripheral equipment. This unit is manufactured for small (3 t) and large (200 t) capacities.

In all of the various systems described above, germination takes place according to the principles applied to the process in a Saladin box. After 1 or 2 days of steeping, as already mentioned, the steeped grain can be cast from the steep "wet" by employing a cleaning auger or even "dry." If the steeping tank is cast out "dry," the time spent in the germination and kilning box would, of course, be longer. It is most beneficial to cast the barley from the steep after 1 day (21–26 h) at a moisture content of c. 38% into the germination and kilning box. The residual heat present in the recently vacated kiln provides the barley with heat. After 12–24 h, the moisture content can be raised to 45–47% through spraying (refer to Section 1.5.3.3). According to the known malting principles, it is possible to produce entirely acceptable green malt within around five and a half days, so that the germination and the kilning processes can readily be incorporated into a weekly cycle of operations. In the case of green malt made from abraded barley, drying could even start earlier if the kiln is "available," which depends on the germination schedule. However, this is, for example, no longer the case with a single heating unit serving five germination and kilning boxes.

"Static" malting systems, such as the germination and kilning boxes discussed above, have facilitated the increase in batch sizes in the range of 150–300 t of barley. The elimination of green malt transport, with all of its concomitant disadvantages, is certainly beneficial. One must nevertheless take into account that – at least with the rectangular units – casting out the steeped barley and stripping the kilned malt cost both time and money. The stress on the building during the kilning process and the subsequent cooling, for instance, when casting out the steep, poses a problem. No further considerations are necessary for germination in these larger units. The conditions during germination as they are currently understood remain unaffected by the system if the fundamental parameters of germination are properly abided by.

Germination-kilning boxes can serve as a logical option for the gradual expansion of an existing, "well-rounded" malting facility, which, as a rule, generally has an oversized steeping capacity. The addition of just one germination and kilning box will, of course, require an entire heating and ventilation system. Therefore, supplementing a malting facility with only one box is not as effective economically as further expansion with two or more would be. However, these surplus costs are certainly less than the construction of another single-deck high-performance kiln because a heating and ventilation system would also have to be added for any expansion of the existing conventional malting equipment.

1.6.2.4 Continuous Malting Systems Older continuous malting plants with smaller capacities are, of course, only of historical significance today. However, several continuous, large capacity malting systems known as "Saturn" have been designed and manufactured. The most recent model has a capacity of 200–240 t/d of barley and consists of two steeping vessels, an outer annular deck that is

perforated for germination and an inner annular deck for kilning.

Rectangular steeping tanks with a depth of 3 m are fed with barley by an adjustable speed conveyor (average output 10–12 t/h). Liquor is added to the steep, and the steeping grain is moved through the 20 m long vessel over the course of five to 7 h by means of a chain conveyor. Compressed air contributes to the cleaning effect at this stage. The grain is pumped over into the next steeping vessel, where the steep liquor is removed and replaced with fresh liquor. The steeping process is repeated at this point for another five to 7 h. The steeped grain is pumped onto the outer annular deck where it commences germination. The steep liquor is removed again, this time with a vibrating sieve. The germination deck has a total area of 1650 m^2 and is divided into four sections. Of these, sections I and IV are about half the size of sections II and III. The volumetric output of the ventilation fans for sections I and IV amounts to 300 $m^3/(t \cdot h)$, while that of the two larger ones is 700 $m^3/(t \cdot h)$. The annular germination deck is moved by hydraulic screw jacks. The duration of one complete rotation can range from 2–15 days, depending on the quality of the barley or the malt. Normally, in practice, it lasts between 6 and 7 days. The air passing through the grain bed is cooled by an adjustable blend of fresh and recirculated air, which is set to the desired temperature using ice water. There are seven fixed augers distributed over the entire area of the annular germination deck. A series of spray nozzles allow for the moisture content to be raised gradually during germination.

The green malt is conveyed to the adjacent kiln with a screw conveyor. The inner ring possesses an area of 4600 m^2. In one rotation per day, 350–450 kg of finished malt/m^2 can be kilned. The annular deck comprising the kiln portion of the system is divided into four zones (each with its own temperature range). An additional section is used to cool the malt, while yet another is reserved for loading the green malt. Zones I and II of the kiln are dimensioned to be larger than zones III and IV. The malt is withered in zones I and II (fan output: 250,000 m^3/h), while the grain is heated and then cured with a reduced volumetric airflow (100,000 m^3/h) in the latter two. The air coming off of zone IV, which is no longer saturated with moisture, is returned to the withering zones. This is also feasible with the air coming off of zone III, depending on its moisture content. The advantages of the system are as follows: a relatively low capacity for the conveyor systems of 8–10 t/h; the dimensioning of the fans and air chillers/heaters for the requisite germination/withering sections; favorable conditions for energy and water savings; and straightforward automation of the individual processes. However, one must take into consideration that large batches of uniform barley must be available for malting. Fluctuations in barley quality can be compensated for by varying the germination conditions; for instance, a change from two-rowed to multi-rowed barley can be offset by accelerating the speed of rotation; however, some carryover does occur.

1.6.2.5 Kilns in Continuous Operation The desire to increase energy savings and, above all, in the case of operations employing a cogeneration plant, to maintain a constant level of heat energy consumption, led to the development of kilns in the 1980s that could operate continuously. However, only the Lausmann *vertical kiln* has persisted; even then, only one was ever constructed.

It consists of four shafts through which the air for drying the malt flows perpendicular to the grain bed. In contrast to batch-wise operations in a vertical kiln, as described in Section 1.6.2.6, the heated air flows exclusively in one direction through the grain bed. This means that the air coming, for instance, off of zone IV, which was heated to 80–82 °C, is then redirected to the front of the preceding zone III, where it is blended with preheated fresh air and attempered to the desired 70–72 °C. The air coming off of this zone is, in turn, directed to the air inlet side of the withering zones, blended with fresh air and split into two streams, namely 60–62 °C in zone II and 50–55 °C in zone I. The air exiting these two zones is completely saturated and has a temperature of 26–28 °C after blending. The remaining heat is transferred to the fresh air being drawn into the kiln by means of a crossflow heat exchanger. Operations are fully automated. The loading and unloading process is controlled by the air-off temperature from zone III. Loading/unloading takes place approximately four times every hour. The temperature can be adjusted as necessary and is usually set at around 42 °C. The column of malt moves every 15–17 min. In order to avoid losses of heat in the air, the cured malt is discharged through a gate into a cooling compartment. The air used to cool the cured malt, in turn, serves to preheat the kiln air. The green malt is in a compartmentalized box equipped with a "Lausmann turning device" on a deck that can be raised and lowered. The green malt is distributed onto the four zones of the kiln decks.

The kiln has four air heaters, which, as described previously, are set to approximately 80, 70, 60,

and 50 °C (these settings are adjustable). The volumetric airflow begins at c. 1500 m^3/(t·h), increasing in each section with the supply of preheated fresh air, to around 3000 m^3/(t·h). The energy requirement for heat generation is approximately 1.9×10^6 kJ/t (0.45×10^6 kcal/t) of kilned malt, while electrical energy consumption amounts to 30 kWh/t. If the system is coupled with a cogeneration plant, the heat energy requirement can be reduced further by one-third.

1.6.2.6 "Classic" Multideck Kilns The *"classic" multi-deck kilns*, which were manufactured into the 1940s, are only occasionally found today. For the sake of thoroughness, they are briefly described below. A detailed description can be found in the previous edition of this book. These kilns are tall, tower-like structures with a relatively small cross section in which two or three kiln decks are arranged one above the other.

The kiln elements as perceived from bottom to top are as follows:

The *heating apparatus* consists of a furnace in the so-called stoking room, which was originally used to burn fuels with a mean calorific value of approximately 20,000 kJ/kg (c. 4700 kcal/kg). They were later converted to automatic oil combustion. But there are also systems heated with steam or hot water. The gases generated by combustion of the fuel flow upward through a flue lined with fireclay bricks into the heating chamber, where the gases are directed into heating tubes with a circular or teardrop-shaped cross section. Depending on the capacity of the kiln, this heating surface is two to eight times the surface area of the kiln deck. The height of this heating chamber plays an important role in the natural updraft through the kiln, as it partially determines the upward flow of the air. The airflow is regulated by means of the corresponding flaps ("cold" drafts) installed upstream from the heating chamber.

There are two or three decks in the kiln made of profile wire. In some cases, the lower deck consists of a perforated sheet metal in kilns designed to produce Munich malt. The height of the spaces above the decks is 2–3 m for the lower deck and 4–8 m for the upper one. The space above the upper deck is shaped like a bottle and opens at the top into the base of an 8–10 m high chimney, which is covered by a helmet-like attachment known as a cowl that is capable of rotating in the wind. In order to avoid excessive heating of the grain on the upper deck, cool air warmed by the brickwork is admitted at a point between the decks inside the kiln.

The inherent updraft in the kiln naturally depended on the height of the grain bed on the upper deck and the physical characteristics of the outside air (temperature and humidity). Therefore, the output of these kinds of kilns frequently fluctuated. A sufficient amount of airflow was assured through the installation of fans, either to guarantee a certain capacity or to increase the output of an existing kiln. As determined by the daily rhythm of kiln operations (2×12 h or 2×24 h), these fans have a volumetric capacity of 1500–2000 m^3/(t·h). The electrical energy consumption is 10–12 kWh/t.

Kilns with two and three decks have automatic turning devices. On the lower deck, a turning device with scoops or blades is installed, while on the upper deck, those with tines are present to loosen the grain bed. For extremely heavy loads, the upper deck is equipped with Saladin-style turning devices.

The characteristics of the multi-deck kilns are as follows:

- kiln deck surface area: 10–200 m^2
- upper deck loading: 30–200 kg of barley as green malt
  - for Pilsner malt without a fan: 30–40 kg/m^2
  - for Munich malt without a fan: 60–70 kg/m^2
  - for Pilsner malt with a fan: 60–70 to 200 kg/m^2
- kilning duration for Pilsner malt: 2×12 h or 2×24 h; for Munich malt: 2×24 h,
  - for three-deck kilns: 3×12 h to 3×16 h
- heat energy consumption: 5×10^6 kJ/t (1.2×10^6 kcal/t), with three-deck kilns, approximately 15% less.

The vertical kiln in its original form represents an interesting design from the 1930s. However, new and improved vertical kilns dating from a later period can still be found in Eastern Europe. The vertical decks, arranged in pairs, are divided into two to three sections (in kilns with two or three decks). In order to imitate the turning in horizontal kilns, which was mistakenly considered necessary, the airflow was diverted by flaps at given time intervals (e.g., hourly). However, this repeatedly raised the moisture in grain that had already dried, which caused a certain amount of hardness or "glassiness" in the kernels. The energy requirements of these kilns, which usually operate on a 24 h cycle, were only slightly below that of the contemporary two-deck horizontal kilns.

1.6.3 Kilning Techniques

Kilning techniques for the production of Pilsner and Munich malts vary based on the following: how the

temperature increases in the kiln and in the malt; how the volume of air passing through the kiln is regulated by modifying the fan speed and its drying effect; the application of fresh air and recirculated air; and, in some cases, turning the malt during the various drying stages in multi-deck kilns.

1.6.3.1 Kilning Pilsner Malt in a Single-deck Kiln Green malt destined to become Pilsner malt is characterized by certain attributes; however, these may fluctuate over a broad range, given today's profusion of malting techniques. The moisture content of the green malt for the production of Pilsner malt is generally between 43% and 48%, and the temperature between 12 and 20 °C. If the green malt is uniformly well modified, then its levels of proteolytic and cytolytic degradation as well as the development of its enzymatic capacity will be less pronounced than that of Munich malt.

In principle, the moisture content of the green malt must be reduced as quickly as possible in order to prevent further growth in the kernels and to limit the formation of enzymes in the interest of obtaining a lighter color. Green malt with a moisture content of approximately 43% releases water readily because the vapor pressure on the surface of the kernel is comparable to that of the surface of open water. In addition, as the moisture on the surface evaporates, the moisture present inside the kernel migrates as a result of capillary forces from the warmer interior to cooler areas on the surface. The steady drop in the moisture content only slows once the limit of 13–14% has been reached (the "critical" moisture content of the malt or the hygroscopic point). In order to continue along the pressure gradient for water vapor between the green malt and the air used for drying the malt – and thus to effectively increase the drying effect – the equilibrium must be shifted constantly; e.g., an effective measure is to increase the temperature of the air for drying the green malt. The rate of moisture removal from the green malt slows still further once the moisture content drops below 10%. On the other hand, a stable equilibrium is achieved at a moisture content of 2%. The moisture only drops below 2% by means of evaporation at temperatures in excess of 100 °C.

In single-deck kilns, the drying process moves layer by layer upward from the bottom to the top. The high volume of airflow through the green malt results in a strong evaporative cooling effect. This allows the drying process to start at significantly higher temperatures than, for example, would be possible in earlier dual-deck kilns. Rapid drying halts the growth of the kernels in the bottom layer of the kiln after only a few hours. However, the enzymes continue to function until a moisture level of approximately 10% and a temperature of 70 °C are reached. This results in an accumulation of low molecular weight degradation products such as sugars and amino acids. Growth in the kernel continues in the upper layer. This utilizes substances generated by the degradation of carbohydrates, proteins, and lipids. These metabolic conversions are still actively taking place in the kiln. Degradation products are also increasing in the upper layer despite the fact that growth is still occurring. With the reduction in moisture from the optimal 40–42% required to sustain growth to 10% and the rise in temperature to above 45 °C, and in rapid succession, to above 65 °C, the conditions are ideal for fostering reactions among the various groups of enzymes (Table 1.12). This further increases the concentration of low molecular weight substances. According to the Mollier h,x diagram, due to the complete saturation of the air with moisture, the air-off temperature is in the range of 22–30 °C, depending on the air-on temperature. The air-off temperature climbs rapidly, and the moisture in the air drops continuously only after the moisture content in the upper layers of the green malt has fallen below the hygroscopic point. Compared to the lower layers, the green malt/withering malt in the upper layers is exposed 10–12 h longer to the range of temperatures and moisture levels at which growth and enzymatic activity can endure. Nevertheless, this is contingent upon careful operation of the kiln, so that the temperatures do not exceed the limits required for the enzymes to continue the degradation of protein and starch. With the airflow at a high velocity and the rapid evaporative cooling during drying, the green malt does not heat up until it has dropped below the hygroscopic point.

As a result, the malt in the uppermost layer of the kiln possesses somewhat better values regarding the extract difference (fine/coarse), a higher ratio of soluble protein to total protein, and more low molecular weight nitrogen than the malt in the lower layer. Furthermore, despite its shorter exposure to the higher curing temperatures, the color of the malt in the upper layer is darker than that of the malt in the lower layer due to its greater concentration of low molecular weight degradation products.

The withering phase is carried out at air-on temperatures ranging from 45 to 65 °C as measured in the hot air chamber (under the deck of the kiln). Although it is possible to start kilning at higher initial temperatures, withering is performed at the temperatures stated above in order

to preserve the optimum volume and friability of the malt. The temperature is maintained at 65 °C until breakthrough is achieved, and the air-off temperature is only 20–25 °C below the air-on temperature. The fan runs at the highest speed; e.g., it conveys air at a volumetric rate between 4000 and 4800 m^3/t of malt per hour. For resteeped malts, this rate may be as high as 5500 m^3/t of malt per hour. This rate increases by approximately 10% during the withering phase because the resistance in the green malt bed decreases as the moisture is removed. Withering and forced drying, i.e., up to the breakthrough, lasts 10–13 h, depending on the moisture content of the green malt, the fan speed, and the temperature sequence.

Malt withered in this way cannot be transformed into typical, aromatic dark malt (e.g., Munich malt). The character of malt that is lighter in color is also determined during the withering phase.

Once breakthrough occurs, the fan speed is reduced in order to limit the amount of excess air and thus to save electricity and heat. The fan speed is reduced incrementally until it reaches approximately 50% of the initial output, i.e., to 2000–2700 m^3/(t·h). Any further reduction is unnecessary because the difference between the individual layers of malt is too large and the top layers would not be sufficiently cured. The kiln is heated to the curing temperature in increments of 5 °C/h or continuously over a period of 2–3 h. A curing temperature of 80–85 °C is maintained for 4–5 h, depending on the desired malt color and the intensity of the preliminary drying process. A graduated approach can be employed for curing very light malts, e.g., 2 h at 80 °C followed by 3 h at 82 °C. The finished malt has a moisture content of 3.5–4.2%, depending on the curing temperature as well as the velocity of the airflow and the quality of the air. Given that the airflow is conducted as described above, the temperature in the uppermost layer of the malt is 2–3 °C lower than in the bottom layer. However, the moisture content of the malt is only 0.2–0.4% higher (refer to Table 1.12).

This kilning method, which only utilizes fresh air, is employed in the production of Pilsner malt. The fan speed can be reduced earlier, at either an air-off moisture content of around 75% or at an air-off temperature of 35 °C, with barley or green malt relatively resistant to an increase in color or when a malt color of 3.0–3.5 EBC is desired. It is also practical to simply employ recirculated air during the curing stage of kilning because it generally possesses a relative humidity of less than 15% once curing begins. In practice, at around 1 h after reaching the desired temperature for curing, recirculated air is increased to a rate of 25%, then to 50%, and, after another hour has elapsed, finally to 75% during the last 2–3 h. The fan speed is simultaneously increased to approximately 80% of its initial speed (3300/(t·h) in the example given above). This helps to balance the temperatures between the upper and lower layers of malt.

Despite the unavoidable loss of enzymes, higher curing temperatures should be applied to coagulate high molecular weight nitrogenous substances, an effect that is considered beneficial. The coagulated proteins will not cause any further difficulties in the brewing process. The beers can be filtered more easily, exhibit a better protein or colloidal stability, and also possess improved foam

Table 1.12 Withering and curing Pilsner malt in a single-deck kiln.

Hours		1	2	3	4	5	6	7	8	9	10
Air-on temperature	[°C]	45	50	55	55	60	60	60	60	65	65
Air-off temperature	[°C]	20	22	23	23	24	24	26	29	33	37
Air-off moisture	[%]	100	100	100	100	100	100	85	70	55	42
Fan output, volumetric airflow	[m^3/h]	4400						4800			4900

Hours		11	12	13	14	15	16	17	18	19
Air-on temperature	[°C]	65	70	75	80	82	85	85	85	85
Air-off temperature	[°C]	45	50	58	68	72	76	78	80	81
Air-off moisture	[%]	31	23	15	12	<10	<10	<10	<10	<10
Fan output, volumetric airflow	[m^3/h]	3800	3200	2900	2500	2500	2200	2200	3000	3300
Proportion of recirculated air	[%]					25	50	50	75	75

properties. High curing temperatures bring about slight changes in the color of the malt if the green malt only contains a small quantity of low molecular weight nitrogen and starch degradation products with a low capacity for entering chemical reactions. In addition, slight changes may result from drying at temperatures below 60–65 °C until breakthrough is achieved, i.e., prior to heating the kiln to curing temperatures. Malt that has been insufficiently kilned was previously considered not to be "kiln-stable," meaning that it was not expected to retain the properties it possessed upon leaving the kiln during the subsequent period of storage. If a malt was not "kiln-stable," it was assumed that the malt would produce wort and beer of a deeper color than expected later on in the brewing process, and the beers would suffer from a low stability. The higher the curing temperature rises above 82–83 °C, the more the color deepens. This phenomenon is attributable to the reactions of substances present in the preliminary and intermediate stages of melanoidin formation. Determination of the dimethyl sulfide precursor can offer information regarding whether the curing process was sufficiently intense. The amount of precursor is linked to the barley and the malting regime; however, it is particularly influenced by conditions during the curing phase of kilning.

In the past, the withering and curing phases were estimated to last approximately 19 h. Modern kiln loading devices (refer to Section 1.6.6.1) and the act of unloading the deck of the kiln in a single motion by tipping it into a suitably dimensioned trough to accept the entire volume of malt have shortened the "dead periods" in kilning to the extent that malt can be kilned and effectively cooled with fresh air in just 21 ½–22 h. This is 10–15% more, which translates into a reduction in fan power and therefore energy savings.

This method of drying in layers and increasing the temperature, which was previously regarded as positive for malt quality, has now been recently examined and deemed to be negative in terms of the degradation and oxidation of lipids. This method promotes the formation of products in the upper layers of malt as it dries. The products formed are aging compounds, which will ultimately lower the flavor stability of the finished beer (refer to Section 7.6.5.5). This led to an attempt to accelerate withering through the application of higher temperatures to dry the malt. Blended air (refer to Section 1.6.3.1) was intended to reduce the difference between the temperatures in the upper and lower layers of green malt in the kiln. This method is able to achieve better results in terms of flavor stability if the concentration of Maillard products is not excessive due to thermal stress.

Curing Munich malt in a single-deck kiln: the process of kilning Munich malt is both more difficult and more complex than the process used for kilning Pilsner malt, since Munich malt is not simply being dried; to be precise, distinct conditions with regard to moisture and temperature must be created. These conditions facilitate further growth of the embryo and therefore allow a greater degree of modification to occur. The primary focus is on increasing the concentration of low molecular weight nitrogenous substances and sugars present in the kernels. These will go on to develop into the natural aromas and color present in Munich malt during the curing phase of kilning. The prerequisite for producing Munich malt full of character is to begin with green malt that is well modified down to the tips of the kernels. It should possess a high moisture content, around 45–50%. When kilning Munich malt, the moisture content of the green malt is reduced very slowly, so that the enzymes can continue to function, allowing the desired chemical and biological reactions and conversions to occur.

In the withering phase, which takes place during the first 6–10 h of kilning, the moisture content in the kernels is reduced from 45% to no less than 20%. This is an important criterion: the moisture content should not be the average in the entirety of the malt being kilned; rather, the moisture content must be no lower than 20% in the lower layers of malt as well. A temperature of 35–40 °C in the malt is optimal for promoting the desired degradation reactions. This stage is referred to as "stewing" or "warm withering." In contrast to the production of Pilsner malt, fresh air is not employed for drying in this stage of kilning. In the production of Munich malt, a mixture of fresh air and recirculated air is used. Drying with fresh air creates a significant temperature difference between the incoming air and the exhaust air as a result of evaporative cooling. When the drying air completely consists of recirculated air in the kiln, the air-on and -off temperatures and the temperature of the malt bed itself even out, becoming more uniform. However, if a blend of fresh and recirculated air is used, the temperature in the malt bed will increase more slowly than with pure recirculated air. The temperature increase, therefore, depends on the ratio of fresh air to recirculated air. The blended air is modified constantly until an equilibrium is reached, but adjustment of the fresh air stream continues throughout the process. This blended air system is largely independent of outdoor conditions; the

proportion of fresh air can vary and determines its effect on the malt. During the withering phase for Pilsner malt, the air-on temperature is selected, so that the air exiting the bed does not exceed a specified air-off temperature. For Munich malt, the air-on and -off temperatures are crucial in bringing about certain reactions.

Temperatures between 35 and 40 °C are considered favorable for the continued degradation reactions in the kernel and the formation of a greater proportion of low molecular weight substances during the withering phase of kilning. This occurs with a blend of fresh air to recirculated air at a ratio of 20% : 80% with an air intake temperature of 50 °C. A fan speed of around 70% of 3000 $m^3/(t \cdot h)$ is sufficient; it is not necessary for the fan to be at full speed. After 4 h have passed, the temperature of the incoming air is raised to 55 °C to further promote enzymatic activity. The temperature of the malt is approximately 40 °C at the same ratio of blended air. At the end of this sequence, the upper layer of the malt still retains its initial moisture content, while that of the lower layer is 20–25%. If this method is used to wither the malt, then the subsequent production of Pilsner malt is not possible. The degradation products favor the development of color and aroma during kilning.

The moisture content is reduced from a mean of 35% to 5% during the drying phase that follows. A period of 6 h is scheduled for drying, which begins by operating the fan at full speed and introducing fresh air into the kiln at a temperature of 60 °C. However, after 2 h have elapsed, it is advisable to continue with the fan at full speed but increase the temperature to 70 °C and switch entirely over to recirculated air for an hour. This aids in promoting stronger enzymatic activity (α- and β-amylase) by balancing the moisture content of the malt at the beginning of curing to the uniform level required in the lowest layer of the malt for the desired chemical reactions to take place. The temperature is maintained at 80–95 °C as drying progresses. Blended air at a ratio of 80% fresh air to 20% recirculated air is employed at the higher temperatures in this range. The air-off moisture content drops to about 10% by the end of this drying phase.

At this point, the malt is subjected to a 5 h period of roasting, first at 100 °C, and then finally at 105 °C in order to generate melanoidins, the substances that give the malt its color and roasted, aromatic character.

Maintaining high temperatures over a longer period is necessary, so that the amino acids that are slower to react, such as valine and leucine, have enough time to do so. The temperature necessary to achieve this is not always the same: well-modified malt which has been processed properly during the withering phase reaches the desired color and also obtains the proper aroma and flavor characteristics at lower temperatures. The moisture content of the malt drops to approximately 2% during the curing phase of kilning. The proportion of recirculated air is gradually increased from 20% to 80% by restricting the input of fresh air. This serves to allow the temperature to become as uniform as possible amid the various layers of malt in the kiln. The fan remains at full speed during this phase. This measure also serves to elevate the temperature of the upper layer of malt to above 100 °C.

The resultant malt is friable and exhibits a uniform color along with a satisfactory aroma despite the abrupt heating and rapid moisture removal in this process. The time required for saccharification in the Congress mash ranges from 15–30 min. The amount of enzyme damage is less than that resulting from kilning on two decks.

Medium-colored malts (Vienna type) are kilned using the same method as Pilsner malt. However, starting at an air-off temperature of 35 °C (75% relative humidity), it is recommended that the temperature be raised slowly, e.g., by 5 °C/h, to the curing temperature. During this time, the fan speed should be lowered in steps, and recirculated air should be introduced once the air-off temperature is around 54 °C. The proportion of recirculated air should be raised from 20% to 80% over the span of 4–5 h. The malt is cured at 90–95 °C for 3–4 h until the desired color is obtained (5–8 EBC units).

1.6.3.2 Vertical Two-deck High-performance Kilns The kilning regime described in Section 1.6.2.2 for a *two-deck, high-performance kiln* with the decks arranged vertically, and a withering and curing sequence requiring a net of 2 × 19 h, transpires as follows: the air coming off of the lower deck also serves as the drying air for the upper deck; the same volume of air is passed through both decks. The air used for withering is not reheated. The drying capacity of the air is reduced compared to operating a single-deck kiln with fresh air alone. For this reason, it is essential to dry the green malt to 10% or less during the withering phase. Otherwise, there is a risk that the drying process for the following batch will be delayed. In addition, the top layer of the malt is still moist, and unloading the malt could cause the temperature in this layer to increase, which would cause damage to the enzymes and cause the kernels to shrivel.

As shown in Tables 1.13 and 1.14, the withering stage begins on the upper deck with a volumetric airflow of approximately 3800 m^3 at 33 °C. The temperature rises to 60 °C over the course of 10–11 h. As the drying stage progresses, the amount of water vapor present on the lower deck decreases. After 14 h, the air-off temperature/intake air is 65 °C. This should not be exceeded to ensure that the withering process is adequately gentle. Consequently, fresh air (attempered beforehand in the crossflow heat exchanger) is supplied to the fan, simultaneously reducing the rate of airflow through the lower deck. When an air-off temperature of 30 °C is reached, the fan output is continuously lowered to approximately 2000 $m^3/(t \cdot h)$ (60%). The exhaust air almost always exits the kiln in the saturated state.

The lower layer of malt has a moisture content of 5.5–6.0% as it is transferred after withering, while the upper layer still retains around 11–13% moisture. The malt is transported from above to the (cooled) lower deck using a screw conveyor that can be raised and lowered vertically. The malt is then spread across the cooled lower deck in layers. Theoretically, the malt at the lowest temperature and with the highest moisture content should be deposited first. However, mixing – at least with the adjacent layers (at a proportion of approximately 20% the height of the layer) – cannot be ruled out.

For this reason, the temperature of the lower deck must be precisely regulated, so that the kernels, which are still very moist, are not damaged. The temperature is held at 60 °C until the temperature above the deck is 54 °C. Only then is the temperature increased to 65 °C, where it is held until a defined Δt is achieved, which in this case is 2–3 °C. Finally, the air is heated continuously until the curing temperature of 80 °C is reached over a period of 4 h. This is followed by 4–5 h of curing at 80–82 °C. The fan speed is lowered after reaching 30 °C. This is the temperature mentioned above for the air exiting the bed of withering malt.

Kilning in this manner has proven itself as a method for producing quality malt. More recent

Table 1.13 Air-on and air-off temperatures in a two-deck kiln.

Hours			1	2	3	4	5	6	7	8	9	10
Air	Inlet, lower deck	[°C]	60	60	60	60	60	60	60	60	60	65
	Outlet, lower deck	[°C]	33	35	37	41	45	47	52	54	57	59
	Outlet, upper deck	[°C]	28	28	28	28	28	28	28	28	28	28
Hours			11	12	13	14	15	16	17	18	19	20
Air	Inlet, lower deck	[°C]	65	65	70	72	78	80	80	80	80	
	Outlet, lower deck	[°C]	61	63	64	65*	65	65	65	65	65	
	Outlet, upper deck	[°C]	28	28	29	30†	30	30	30	30	30	

*Starting here, fresh air (prewarmed with a crossflow heat exchanger) is introduced to prevent the temperature from exceeding 65 °C.
†The fan speed is lowered in steps once the temperature reaches 30 °C.

Table 1.14 Temperatures in the four drying zones of a vertical kiln.

Zone		IV		III		II		I	
		Inlet	Outlet	Inlet	Outlet	Inlet		Inlet	Outlet
		Beginning to end			Beginning to end			Beginning to end	
Air temperature	[°C]	80	75–79	70	37–42*	60		50	26–29
Volumetric fan output	[$m^3/(t \cdot h)$]	1500		2250		3000			

*The temperature may be adjusted to initiate the process of loading or unloading the kiln.

designs allow the kiln to be loaded and unloaded more rapidly. This makes a total processing time of 2 × 20–21 h possible. The color of both the malt and the boiled wort is very light. The friability is excellent, and the DMS content is low. It is likely that the green malt on the upper deck does indeed undergo further modification; however, only slight differences have been measured between the upper and lower layers of the withered malt.

1.6.3.3 Parallel Two-deck Kilns with Variable Airflow Systems The method described in Section 1.6.2.2 for *parallel, two-deck kilns with a variable airflow system* differs in that the malt remains in one position over the stages of withering and curing. Furthermore, the exhaust air is no longer fully utilized once breakthrough has been achieved. Instead, it is supplemented with fresh air, and the blended air passes through a second heating device to raise it to 45–50 °C, the temperature at which withering is carried out. Approximately 22 h is scheduled for withering. Although the fan may be dimensioned to deliver a volumetric output of 2500 m^3/(t·h), it is generally not operated at the maximum possible speed but instead is frequency controlled. This increases the capability and flexibility of the system to react to the moisture content of the green malt and the rate at which drying proceeds (Δt above/below the deck). As a result, the temperature rises continuously to 60 °C, and the air-off temperature does not exceed 30 °C. The air coming off of the malt bed is also fully saturated. The moisture content at the end of this period is 6.5% below the deck and 12–14% above it. After the kiln deck has been unloaded and then reloaded with green malt for withering, the drying stage continues with the temperature slowly increasing to 65 °C and a fan speed of 1500 m^3/(t·h). This air exiting the malt bed is reused in the withering phase. Subsequently, the temperature is continuously increased from 80 to 85–86 °C for curing. The fan speed must be continuously adjusted as well based on the temperature difference below and above the deck. Higher curing temperatures do not increase the energy requirement because the air from the withering stage is fully utilized.

Concerns were expressed regarding the long periods of occupancy and overmodification during withering, e.g., in the upper layer of the malt. These also included reservations about considerable differences materializing between the upper and lower layers of the bed. None of these concerns have proven correct. Cytolysis is certainly more advanced in this configuration compared to single-deck kilns, particularly in the upper layer. However, neither the soluble nitrogen nor the amino nitrogen levels increase in the upper layer since it is apparently consumed by the embryo for the creation of new tissues. The values for malt color and boiled wort color varied only slightly, as did the concentrations of DMS.

The issues with increased lipid metabolism in the upper layers of the (unturned) malt described in Section 1.6.3.1 are also applicable here.

1.6.3.4 Triflex Kilns The *Triflex kiln* described in Section 1.6.2.2 is based on the same principle for regulating the airflow during the kilning process; however, as previously mentioned, one deck in the kiln is loaded with 45% of the green malt, while the other receives 55%. Due to this arrangement as well as to the higher volumetric airflow, the duration of withering and curing on the first deck is only 19 h when following the same temperature sequence from 55 to 80 °C. For a more heavily loaded deck, the withering phase alone lasts 19–20 h with 30–31 h required for the entire kilning process. Air coming off of one of the three decks is always available for the duration of the withering phase. No problems have been encountered as a result of the slight differences mentioned earlier for malt that has been withered for a shorter or longer period.

1.6.3.5 Vertical Kilns *Vertical kilns* are loaded from a fully climate-controlled, single-day germination box.

The withering phase is divided as indicated in Table 1.13, into a 50 and a 60 °C segment each (refer to p. 84).

The exhaust air is discharged collectively. Breakthrough occurs in zone III at around 42 °C; the air-on temperature is approximately 70 °C. Once the temperature rises to the target value of 42 °C, it triggers migration of the malt down to the next zone, where the temperature is reached by mixing the air that is passing through this section of the green malt. The temperature is around 33 °C at the upper portion, which is adjacent to zone II, and around 65 °C at the lowest portion immediately adjoining zone IV. Temperatures above 80 °C are possible, but the temperature differences between the individual zones must be adjusted to be correspondingly higher. The kiln functions very well, because all of the air flows through the kiln in the same direction. The differences between the air-on and -off sides are negligible. On the other hand, the 24 h interval encountered when processing single-day boxes can naturally lead to certain differences in the modification levels for the first and

last batches if the green malt is not kept cool or is not cooled effectively during this time. These differences can easily be offset in a silo designed to store kilned malt. The analysis data are the same as those measured in a single-deck kiln operated in parallel.

A kiln operating continuously can be utilized to process a relatively constant quantity of malt per day. Less-common types of malt and specialty malts should be withered and cured in conventional kilns due to the difficulties inherent in switching between types of malt – as encountered in every continuous system.

One problematic aspect of a continuously operating kiln is that the temperature of the drying air in zone I always remains within the range of the 50 °C intake air and the 26–27 °C outlet air. This creates favorable conditions for the growth of microorganisms such as molds, bacteria, and yeasts. It is therefore necessary to clean this part of the kiln periodically due to its humid atmosphere. Zone I must therefore be able to be separated from the others, so that it can be cleaned with high-pressure sprayers after allowing it to run empty.

1.6.3.6 Operating a Combination Germination Box-kiln This design functions according to the same principle as a single-deck, high-performance kiln. However, the height of the green malt bed (around 30–60% higher) requires a longer drying period per m^2 of deck area at the same fan speed (refer to Section 1.6.2.5). A volumetric air flow of only 2,500–3,500 $m^3/(t \cdot h)$ is possible without any additional power consumption due to the higher specific loading of the deck. The additional height of the bed extends the withering period, which lasts from 16 to 24 h, depending on the fan speed. Assuming that the withering stage takes 24 h, the following schedule can be applied.

Withering is performed for 4 h at 50 °C, 4 h at 55 °C, and 10 h at 60 °C, followed by a number of hours at 65 °C, i.e., the time necessary for the air-off temperature to rise to approximately 32 °C. The kiln is heated from 65 to 80 °C in 4 h, followed by curing for 5 h at 80–85 °C. This brings the total time required for withering and curing to 31–33 h. Regulation of the fan speed commences once the air-off temperature reaches 40 °C. The difference between the air-on and -off temperatures is still 30 °C at this time. When the air-off temperature reaches 52 °C, i.e., before curing begins, the flap is opened to allow recirculation of some of the air exiting the malt bed. The proportion of recirculated air approaches 50–70% at the end of kilning.

With a rectangular germination box-kiln that is 40–50 m in length, the germination phase is concluded by changing the conditions to those required for the next phase, i.e., withering. The entire box must be heated to a uniform temperature, which can be monitored by measuring the temperature differences below the deck between the kiln air inlet and the opposite end. This is achieved after 4–5 h of withering. These differences in temperature do not exist in boxes with crossflow ventilation or in round units.

There are no significant differences in the analysis data from the malt samples taken from the top and bottom layers of green malt despite the "phase shift" that occurs between germination and withering. The building is so effectively insulated that the box undergoing curing only exhibits a temperature difference of 2 °C to that of the wall of the neighboring box where germination is taking place. The air conditions present in the germination box remain completely unaffected. The freshly cured malt should be cooled slowly, especially in an effort to reduce the inevitable thermal stress on the building material. This can be carried out by turning off the furnace while still allowing the recirculated air to flow until it reaches a temperature of approximately 60 °C. Thereafter, fresh air is used to further cool the malt.

The turning device is not engaged during the processes of withering and curing. It is only utilized once at the end of the withering stage for moving the malt along the breadth of the "cast" to expose the zones not entirely accessible by the drying process.

Two combination germination box-kilns are positioned in such a way that the air coming off of one box at the end of withering, i.e., breakthrough, can be used to warm the air for withering in the neighboring box, serving the same function as described in a two-deck kiln. One should note that the periods of 24–28 h each that are required for withering and curing do not result in overmodification in the upper layers of the malt, despite the high specific loading rate. This is attributable to the fact that the embryo continues to generate new compounds from the products of the enzymatic reactions. However, the lengthy duration of the process and the higher germination temperatures have the effect of improving cytolysis, thus bringing about a corresponding decrease in β-glucan content.

1.6.3.7 Operating a Traditional Two-deck Kiln The operation of a traditional two-deck kiln (refer to Section 1.6.2.6) is described briefly below. Additional information can be found in earlier editions of this book.

When producing *Pilsner malt* in this type of kiln, rapid removal of moisture, especially when employing natural air currents, is only possible if the green malt is spread out in a thin layer (approximately 35 kg/m^2). If a fan is used to create the airflow, the layer of green malt can be double this quantity.

The withering process on the upper deck takes place in two stages:

1. Moisture removal from 45% to 30% at an incoming air temperature of 35–40 °C (below the upper deck).
2. Moisture removal from 30% down to 10% at a temperature of 40–50 °C (also measured beneath the upper deck).

Whether this moisture content is reached after 12 h (also applicable to a 2 × 24 h kilning operation) is apparent by the rootlets falling off the kernels and the formation of depressions in the malt bed on the upper deck.

Moisture continues to be removed from the malt on the lower deck until it reaches a content of 3.5–4%. At this point, the temperatures beneath the deck are around 50–60 °C. When withering the green malt that has recently been spread over the upper deck, one must ensure that it receives the full volume of air available. After gradually raising the temperature in a series of steps to 70 °C and holding this temperature for 2–3 h, the air is then heated to 80–85 °C also over the course of 2–3 h. It is held there for 3–5 h (the temperature is measured in the malt bed, approximately 1 cm above the deck). The temperature of the air over the lower deck is reduced to one conducive for withering with intermittent drafts of fresh air. Turning the green malt ensures that it is uniformly distributed over the deck prior to commencing the withering process. However, the malt is not turned during the drying stage because the unavoidable drying and remoistening of the malt will cause the kernels to shrink. Turning is not necessary, even on the lower deck – at least not until the heating of the air to the curing temperature begins. The malt is turned on an hourly basis until the curing temperature is reached and then constantly thereafter. For technical reasons, a 2 × 24 h operation is preferred. In some cases, the fan speed is either significantly reduced or completely turned off after reaching a moisture content of approximately 10–12% during withering.

In the past, the *curing of Munich malt* was supplemented by withering on a well-ventilated withering deck, on an open surface either in front of or above the kiln. This involved leaving the malt for one or 2 days at cooler temperatures in order to improve modification.

This method was abandoned due to space restrictions and for labor-related reasons. The entire withering stage is performed on the kiln deck, which was originally constructed for kilning Munich malt.

The withering process in a two-deck kiln takes place in three stages:

1. The moisture content is reduced from around 45% to 20–25%, and the temperature drops to 40 °C over a span of 12–14 h. Only a weak level of airflow should pass through the kiln. Turning should be done every 2 h to slow the rate of drying.
2. Intensive degradation processes occur at temperatures of 50–60 °C if the moisture content is maintained at 20–25%. This stage lasts around 10 h with the airflow either limited or stopped. The malt is turned hourly.
3. On the lower deck: the moisture content decreases from 20–25% to about 10% over 12 h; the temperature is 50–55 °C; the airflow is as described under stage 1; the malt is turned every 2 h.

The entire withering stage takes a total of 36 h. Heating to curing temperature requires 6–7 h and reduces the moisture content of the malt to 5–6%. The ducts are closed, which when opened cause an updraft, pulling the air up and out of the kiln; however, since they are closed, this does not occur. Curing takes place at 102–105 °C over a period of approximately 5 h. The temperature between the decks must not exceed 70–75 °C. The turning device runs every half hour or continuously in larger kilns. Temperature stratification occurs in the kiln, which results in a greater difference between the temperatures under and over the deck. This stratification in the kiln not only enables the curing temperature to reach 102–105 °C on the lower deck but also allows the moisture in the air to remain sufficiently high there.

As a result of the inevitable temperature differences in the system, this dark (Munich) malt is less homogeneous than malt produced in a single-deck kiln. The target color of the malt is 12–15 EBC in order to avoid the burnt aroma notes found in some darker malts. Around 1% roasted malt can be added to the grain bill to achieve the desired color in dark beers, e.g., a color of 50 EBC.

1.6.4 Monitoring and Automating Kilning – Kiln Maintenance

1.6.4.1 Monitoring Kiln Operations A number of *measures are employed to monitor* single-deck,

high-performance kilns and germination boxes during operations. The following data are transferred to a chart recorder: the air-on temperature (under the deck in the hot air chamber), the air-off temperature above the deck, the temperature in the malt bed at several points (if applicable), the output of the fan (in % of the maximum output), and the position of the recirculated air flap. For dual-deck kilns and variations on that design, the air temperature between the decks is measured along with the proportion of fresh air blended with recirculated air, the air intake for the withering deck, and the output of the withering fan, among others. The data from the crossflow heat exchanger should also be recorded.

Several kinds of data are recorded during the commissioning of the kiln and as part of the regular monitoring during operations. These include measurements of the malt temperature at various points in the kiln and at different heights, the decrease in the moisture content and the uniformity throughout the lot in addition to the measurements of moisture content, color, and the time required for saccharification. If necessary, further analysis of the uppermost and bottom layers of malt may also be performed. Anemometers can be employed to control air flow at various stages in the kilning process, the distribution of the fresh air and recirculated air streams, and the uniformity of the loading process. The integrity of the seal on the movable portion of the tipping decks can also be verified with this device. Furthermore, the heat and the power consumption for each kiln should be recorded on a daily basis.

1.6.4.2 Automating Kiln Operations *Automating kiln operations*: the measured values, i.e., the air-on and -off temperatures, and less commonly the moisture content of the air exiting the bed are the data used to automate the kilning process. For example, under automated control, after reaching the end of withering process, the final temperature can be held as long as necessary until a preset air-off temperature is achieved. At this point, the programmed heating of the kiln to the curing temperature begins. Upon reaching further, freely selectable air-off temperatures, further operations are carried out, e.g., regulating the fan output, the blending of the recirculated air, and limiting the kilning time.

In modern, computer-controlled kilns, the target moisture content of the green malt is entered as well as the temperature program and the desired length of the withering period until breakthrough occurs. The frequency-controlled fan speed is set according to the parameters mentioned above and the progress made in drying the malt; after reaching the breakthrough, the automation provides "recirculated air" for the freshly loaded kiln, while it also switches over to the kiln fan. All of the data listed above are depicted graphically and can be printed out.

1.6.4.3 The Maintenance and Servicing of Kilns The maintenance and servicing of the kiln encompasses the machinery responsible for firing the kiln and any equipment involved in heat transfer. This includes the fan, the kiln decks, the slide gate valves, and the measuring, switching, and control devices.

1.6.5 Energy-Saving Measures

1.6.5.1 Thermal Energy Requirements The *annual thermal energy requirement* for a direct-fired single-deck high-performance kiln is 4×10^6 kJ/t (0.95 million kcal/t) of finished malt (refer to Section 1.6.2.1). The electricity required to run this type of kiln is approximately 32 kWh/t.

Various methods have been proposed for lowering the energy consumption of the malting process since it comprises a considerable portion of the cost of malting operations. Some have been shown to be impractical, such as removing the moisture from the air for drying the malt by means of lithium chloride desiccants, the utilization of heat pumps, and the production of malt with a higher moisture content, e.g., by curtailing the curing period and by the premature application of recirculated air after the breakthrough occurs. These techniques have often had a detrimental impact on the character of the malt (and the beer); the DMS content was also problematic.

1.6.5.2 Prewarming the Incoming Air *Heat energy savings by prewarming the incoming air*: this can be achieved by mounting the air-cooled condenser of the refrigeration equipment in the intake shaft of the kiln. The flow rate of the air over the condenser should amount to 60–80% of the air required for kilning. The flow rate must be able to be adjusted independent of the condenser. The percentage of the heat energy savings ranges from 8–12%, while the electricity consumption for the entire plant increases by 10%. Another aspect to bear in mind is that the refrigeration system might not be in operation in colder seasons.

Crossflow heat exchangers (constructed of glass plates or glass tubes) are positioned in the exhaust air shaft of the kiln. The exhaust air passes through

heat exchanger, warming the incoming air, which results in an average savings in heat energy of 30–33%. The efficiency of the heat exchanger is approximately 80% during withering and 70% when the kiln is heating up to curing temperatures. On the intake air side, a resistance of 15 mmAq causes the kiln fan electricity consumption to increase by around 10%. One must ensure that the exhaust air and the fresh air do not mix in an unregulated manner.

The additional electricity consumption is also present in summer when the energy savings gained through usage of the heat exchanger are relatively minor.

The heat exchanger must be cleaned twice per year. The glass tubes should be examined for any visible damage, such as breakage and faulty seals of any kind, and if these are found, they must be repaired immediately. Depending on the source of the waste heat, these can potentially introduce exhaust fumes to the process air (nitrosamine formation).

Heat exchangers outfitted with heat transfer media (e.g., glycol) are mounted at the air intake and exhaust air vents. Glycol is pumped through insulated lines between the two heat exchangers. The savings are somewhat lower than those associated with a crossflow heat exchanger and are dependent on the efficiency of the respective heat exchanger. The power consumption of the pump must also be taken into account. Other factors may also influence the conditions in this system, such as kiln construction and statics.

1.6.5.3 Blended Air *Blended air*, i.e., a mixture of fresh and recirculated air, may be used in kilning if the outside temperatures are below 20 °C: the necessary volume of recirculated air is blended with the fresh air to achieve a temperature of 20 °C at the air intake. With an air-on temperature of 60 °C, this yields an air-off temperature of 30 °C. The volume of blended air can be automated through computer control of the flaps and amounts to an annual savings of 6.5%. This technique is advantageous when combined with a crossflow heat exchanger (see above).

1.6.5.4 Insulating the Kiln *Insulating the kiln*: the radiant heat losses from free-standing kilns can vary from 8–12% for small kilns to 4–6% for large kilns, depending on the area, loading height, and climatic conditions.

1.6.5.5 Efficient Utilization of the Air The use of *two-deck, high-performance kilns*, with the decks arranged above or next to one another (e.g., air-reversing kilns), allows for the complete utilization of the air from the kiln after breakthrough is reached. For this reason, the curing temperature and intensity no longer play a role in energy savings. In conjunction with a crossflow heat exchanger, an energy savings of 45% is feasible. The same amount of savings can be expected with a Triflex or continuous vertical kiln.

1.6.5.6 Heat Pumps The original version of the heat pump system consists of an evaporator installed in the exhaust air shaft; a heat pump and a condenser are located where the air enters the shaft. The compression heat pump is powered by an electric motor or an Otto engine. The heat generated in operating the motor and the resultant radiant heat can be transferred to a heat reservoir system, which can then be employed to supply heat to the kiln. The air passes through a heat exchanger before entering the kiln. The air resistance created by the heat exchanger increases the amount of electricity necessary to power the kiln by 8.75 kWh/t of finished malt. Operation of the compression heat pump requires 80 kWh/t of malt. A heat savings of 40% is possible through the usage of the heat exchanger. The combination of a compression heat exchanger and cogeneration plant is considered state of the art. After the fresh air is prewarmed by the crossflow heat exchanger, the condensers in the heat pump are increased to the temperature of the air, raising its energy potential. The cogeneration unit produces electricity, and the heat liberated through this process is recovered and utilized to heat the air in the kiln. Both of these units work in parallel, delivering energy economically in spite of fluctuating prices for gas and electricity.

1.6.6 Additional Tasks Associated with Kilning

These include loading and unloading (emptying) the deck of the kiln.

1.6.6.1 Conveying the Green Malt Green malt is conveyed to the deck of the kiln by mechanical or pneumatic systems. The green malt is moved by a system of screw or drag chain conveyors. The kiln is *loaded* via a swivel arm to ensure the least amount of energy usage. Centrifugal belt conveyors are also utilized for this application. The most important aspect in kilning without turners is that the layer of green malt is of the same depth and density because ventilation of the bed will otherwise not be uniform.

New automatic systems transfer the green malt from above into a screw conveyor able to swivel horizontally. This screw conveyor moves the green malt outward until a level sensor is activated, which then initiates the movement of the arm. The system distributes the green malt in a completely level and uniform fashion. The bed is deposited very loosely on the deck of the kiln.

1.6.6.2 Emptying the Kiln *Emptying the kiln* of malt is accomplished with a shovel on a pulley system or with tilting decks, the best and simplest methods. The malt may also be removed by means of the kiln loading/unloading systems mentioned above. These rely on horizontal screw conveyors to move the malt to drag the chain conveyors installed along the width of the kiln deck.

1.6.7 Handling of Malt After Kilning

The process of cooling and deculming the malt is described below.

1.6.7.1 Cooling the Malt The malt can be *cooled* in a high-performance single-deck kiln through 30 min of ventilation with unheated air (at ambient temperature). The prerequisites described in Section 1.6.3.6 must be observed in a germination-kilning system. This is not possible with multi-deck kilns. In smaller kilns, the malt rapidly cools as it is transferred through the trough for removal as well as during the process of deculming and cleaning. In larger kilns, the malt must be placed in a cooling hopper to achieve the necessary drop in temperature. If the malt is not cooled properly, the enzymes can be damaged, the color darkens noticeably, and the flavor of the beer is negatively impacted. The malt cools down to a certain degree on the way to be cleaned and during the deculming process itself. However, a malt temperature of around 35 °C is often sustained in higher performance kilns. Malt at this temperature cannot be stored immediately because the large mass of malt will not continue cooling in the silos. Malt should first be stored after its temperature has reached 20–25 °C.

1.6.7.2 Deculming *Deculming* must take place soon after the kiln deck has been unloaded because the hygroscopic rootlets take up moisture quite rapidly. Once the culms have taken up moisture, they cannot be entirely removed from the malt. Incomplete deculming is simply not acceptable, since the presence of these rootlets ultimately deepens the color of the wort. They also impart a bitter flavor to wort and the finished beer, in addition to the undesirable, rapid uptake of moisture by the kilned malt.

Deculming the malt takes place in special deculming machines, which consist of slowly rotating sieve drum. A paddle rotates inside of the drums at a higher speed, breaking the rootlets off without damaging the malt kernels. The culms fall through the sieve drum into a screw conveyor, which transfers them to another screw conveyor. The culms are deposited in bags or are moved to a silo dedicated to the storage of malt culms. The malt leaving the kiln is ventilated quite rigorously to eliminate lightweight impurities. The reduced friction on the malt in single-deck high-performance kilns results in less abrasion compared to multi-deck kilns with their turning devices. The deculming machine must be dimensioned to the same capacity with regard to throughput as the conveyors delivering the malt from the kiln. A preliminary deculming screw auger can also be installed at this point.

Deculming screw augers have proven effective for processing large volumes of malt. These devices consist of a slotted sheet metal trough with a screw turning at the appropriate incline to bring about deculming. The friction between the malt kernels causes the culms to break off. The culms fall through the slots and are collected in a trough extending along the entire length of the auger. Once in the trough, the culms fall into a series of cones mounted at its base. These cones have outlets leading to supports upon which sacks are hung. Instead of sacking them up, the culms can also be transported pneumatically or via a screw conveyor for deposition.

A pneumatic malt culm separator divides the malt and the culms leaving the deculming screw auger. It can also be inserted into the process stream and serves to break off the rootlets as the malt passes through it. The serpentine route of the conveyor is furnished with a crosshatch pattern of grooves on its surface. The malt leaves the transport route and enters a large separator (refer to Section 1.2.3.6) where the heavier malt is separated from the lighter malt culms. An additional cyclone situated downstream from the separator carries out the final step of completely removing the culms from the malt. From here, the air can be sent to a bag filter for purification, if needed. This high-performance, dust-free operation is an advantage of this system. The malt culms are a valuable waste product of malting, amounting to 3–5% of the total weight of the malt. Malt culms are sought after as feed for animals due

to their high protein content (around 24%). The culms are sold in milled form or as pellets.

1.6.7.3 Polishing Malt is polished immediately prior to leaving the malting facility or its use in the brewery. Polishing removes any remaining rootlets, protruding husks, or dust that may be present on the malt. This improves the malt yield, enhances its appearance, and produces a purer flavor. The polishing machines are similar to deculming devices. In place of the paddles in a deculming machines, there are brushes. Vibrating sieves are also used for this purpose. Excessive polishing should, however, be avoided. For this reason, polishing machines are generally adjustable to a variety of settings. The waste resulting from polishing usually adds up to between 0.5% and 1.5% and depends on the type of machine and the distance the malt is conveyed. The waste always contains a fraction of the grits, which can be recovered with specialized equipment and returned to the malt after polishing. The process of polishing is of significance when tax is levied on malt.

1.6.8 Storing Malt and Maintaining Malt Stores

Malt should be stored for a certain amount of time before being utilized in brewing. If freshly kilned malt is not stored prior to its use in the brewhouse, it may create cloudy or opalescent wort and cause difficulties in lautering and fermentation, ultimately influencing the appearance, flavor, and foam properties of the beer. If "young" malt is employed in the brewery too soon, a portion of the enzymes will not be available because they have not yet overcome their stasis due to heat exposure during kilning.

The malt inevitably absorbs a slight amount of moisture under proper storage conditions causing the colloid complexes of proteins and gums to recover their hydration water.

The uptake of moisture also causes the husks and the endosperm to lose their brittleness, allowing the malt to be milled more easily. An increase in the moisture content leads to a certain amount of respiration in the kernel, producing carbon dioxide and water vapor. A period of storage improves undermodified malt or malt that has been cured at very high temperatures. This improves the yield and allows the malt to be processed more easily. The analysis data show no adverse changes in malt with a normal or higher degree of modification after storage for six months at 25 °C. Its characteristics in the brewhouse and the quality of the resultant beer also remain unchanged. Moreover, even malt stored under these conditions that was less thoroughly cured with a moisture content greater than 5% shows no evidence of change. However, storage at 30–35 °C does have a negative influence on malt color, particularly in malt with a higher moisture content.

The activity of lipoxygenase enzymes in malt declines during storage. It decreases by 30–40% after a storage period of 110 days at a low temperature of 7 °C. If the malt is stored at a higher temperature, at around 23 °C, the activity is reduced by 60–70%. An increase in mono-, di-, and trihydroxy fatty acids does occur; however, this does not appear to have an effect on the properties of the beer.

Conventional analysis data show virtually no change in Munich malt under proper storage conditions, e.g., no increase in the moisture content. Volatile aroma compounds, such as aldehydes, ketones, alcohols, esters, lactones, and furans, as well as nitrogenous heterocyclic compounds, remain constant within the normal variation between two lots of kilned malt. The analysis data and the flavor of the wort and beer produced from samples of this malt are identical. The flavor stability of beers produced from Munich malt after a period of storage was somewhat better. These results do not conform to data collected earlier. One can assume that the Munich malts of the past possessed an elevated moisture content, which in turn, caused their properties to change.

The hydroxy acids do not undergo significant change in malt stored for six months at 20 °C, but the concentration of di- and trihydroxy acids did increase considerably. Despite this, there was no detectable impact on the flavor of either fresh or aged beer samples.

Previous reports in the literature, especially those from WWII and the years that immediately followed, provide evidence that storing malt at a moisture content around 10% is damaging to the properties of malt. In addition, there is potential risk due to infestation by pests.

With this in mind, an excessive uptake of moisture should always be avoided when storing malt. Thus, the exposed surface of the malt should be kept to a minimum during storage.

Malt can be stored in granary lofts, bins, or silos.

1.6.8.1 Malt Storage The *storage of malt on the deck of lofts or in granaries* is still encountered from time to time in smaller malting operations. However, the practice of storing malt over broader

surfaces is not favorable, because it results in a higher moisture uptake. Furthermore, the danger of infestation with pests is too great. One remedy, although not very effective, is to cover the malt with tarps or sheets of plastic.

1.6.8.2 Malt Storage in Bins *Storing malt in bins* is preferable since this minimizes the exposed surface area. Malt can be stored at heights of 3–4 m if the structural requirements are fulfilled. Wooden malt storage bins should have as few joints as possible; some are even lined with sheet metal. Malt storage bins should be emptied completely at least four times per year, a procedure that usually requires manual labor.

1.6.8.3 Malt Storage in Silos *Silos* are the only practical and suitable solution to *malt storage*. They offer the advantage of a large volume and a small footprint, while keeping the malt dry and providing optimal pest control. Silos are made of reinforced concrete or steel sheets; sometimes, they are constructed from prefabricated elements. Reinforced concrete silos possess the advantage of lower thermal conductivity, but they are heavy and are also not mobile. It is essential that the silos are left empty for a sufficiently long period after construction, so that the material can bind and dry, thus avoiding any damage to the malt. Steel silos are constructed with rings of a suitable diameter and are bolted together. Alternatively, silos may be constructed of prefabricated elements, which offer the advantage of rapid construction and immediate use. Due to their relatively light weight, the silo can also be relocated. The risk of condensation accumulating during storage of a dry product such as malt is unlikely at Central European latitudes. The silos should be dimensioned, so that individual lots of malt can be stored separately according to color, degree of modification, and provenance. Separate mixing cells are frequently employed for combining different malts to create a uniform blend. Silo cells of a smaller capacity (50–150 t) are capable of dispensing precise quantities of malt to be sold or utilized directly for brewing. Dispensing malt from the silo is done with adjustable slide gate valves or through measurement and blending devices that allow adjustable percentages of malt to be released from different cells and combined. Grain spreaders are used to prevent the malt from separating based on the kernel size when filling larger silos. "Denny spouts" or several discharge spouts on a single silo ensure that they are emptied uniformly. Broken malt kernels must be expected with malt storage in silos. Malt with an extremely high degree of modification and broken husks due to huzzars also tends to fragment more easily, resulting in greater amounts of particulates due to abrasion.

Storage in a silo should span a minimum of four weeks. There is no reason that malt cannot be stored for longer periods, e.g., one to two years if the malt is cool and dry when it is transferred to the silo.

Malt that has taken up too much moisture can be dried in a kiln to improve its milling properties. Excessive moisture can be removed, but the effects caused by enzymatic activity during storage cannot be reversed. These countermeasures generally offer little in the way of a remedy.

If barley malt has been produced from unevenly germinating kernels, it may be beneficial to separate the resultant glassy kernels using a special sorting device, which separates malt kernels according to their weight. This allows the well-modified and therefore lighter weight malt to be separated from poorly modified, heavier malt. The tables used to sort the malt are referred to as *Aschenbrödel* in German (or "Cinderella" in English). With the proper adjustment and operation, the tables classify the malt seamlessly into fractions. These can process up to 2 t/h of malt.

Destoning devices, which function on the basis of air flowing through vibrating sieves arranged to create an incline, are used to separate stones from malt; however, they can be adjusted to sort out glassy kernels as well. Throughput rates can reach as much as 6 t/h (refer to Section 1.2.3.4).

1.7 Malting Losses

The transformation of barley during steeping, germination, and kilning also includes a change in the volume-to-weight ratios in the products (steeped grain, green malt, and kilned malt) compared to its initial state. These can be summarized as in Table 1.15.

The space needed for intermediate products is an important criterion to consider when dimensioning the equipment and planning the overall area required for the malting process.

The primary emphasis is on determining the quantity of malt that can be produced from a specific quantity of barley (100 kg). The malting losses comprise the difference in the quantity of malt versus the quantity of barley used to produce it. The calculation of malting losses commences at the onset of steeping. Losses due to cleaning, sorting/grading, and storage are not taken into

Table 1.15 Changes in the volume and mass of barley over the course of the malting process.

	I: from 100 hl of barley		II: from 100 kg of barley
Barley – beginning of steeping	100 hl	(16% moisture)	100 kg
Barley – end of steeping	145 hl	(45% moisture)	155 kg
Green malt	220 hl	(48% moisture)	147 kg
Kilned malt	118 hl	(3.5% moisture)	78 kg
Malt in storage	120 hl	(4.5% moisture)	79 kg

account, only the cleaned barley destined for malting figures into the calculation.

Barley entering the steep contains 12–18% moisture, while the malt produced from it only possesses a moisture content of 2–4%. The losses calculated from these figures are referred to as "air-dried losses." These range from 16–25% and, aside from the physical losses during germination, may vary widely, depending on fluctuations in the moisture content of the barley and malt. Losses are understandably an important economic factor in the production of malt.

The difference between the moisture content of barley and that of the malt is a loss incurred due to the significant reduction in the moisture content of the malt. The figures are substantial and generally amount to 10–16%.

Because the reduction in moisture content is only an apparent loss, malting losses are expressed in terms of dry matter in order to accurately characterize the true losses incurred during malting. The dry matter is calculated using the quantities by weight of the barley and the malt. The *losses calculated on the basis of dry matter* range from 5–12%. Losses of 8–10% can be assumed for malt produced using conventional malting techniques.

The total malting losses based on dry matter – without taking the losses in the substance of the malt during storage into account – can be separated into three groups: losses due to steeping (approximately 1%), respiration (around 5.2%), and germination (approximately 3.8%). This amounts to a total loss of 10%.

However, malting losses can vary greatly in each of the individual stages of production.

1.7.1 Losses During Steeping

As the barley steeps, inorganic and organic substances are leached from the husks. Floating barley kernels (floaters) do not count as a loss because they are collected, dried, and sold. A long immersion steep, possibly coupled with an intense washing of the grain, causes more leaching to occur than steeping with only short periods of immersion. A pneumatic steeping regimen is associated with respiration losses of 0.5–1% (dry matter); however, these losses only become apparent after the malting process is complete.

If steeping is replaced with another method, such as through usage of a grain cleaning auger and even spray steeping in the germination box (refer to Section 1.3.4), the steeping losses will, of course, be lower. A portion of the impurities, which are not removed during the augmented cleaning of the barley, accumulate with the other materials collected as a result of abrasion during dust removal and the deculming processes.

1.7.2 Losses During Respiration and Germination

As a rule, both of these losses are determined separately despite the fact they are influenced in a similar manner by the conditions during malting.

The *losses due to respiration* are 4–8%. Respiration losses come about through the conversion of starch and fats to CO_2 and water. These losses cannot be reduced beyond a certain level.

Germination losses fall between 3% and 5% for malt produced with conventional malting techniques.

The scope of both types of losses hinges upon the prevailing germination conditions. Losses are incurred during steeping (depending on the method), during germination, and even in the malt kiln.

The total malting losses are dependent on the following:

(a) The moisture content at which germination takes place: the higher the moisture content, the more the kernel undergoes respiration. This brings about more growth in the embryo, which in turn results in more losses.
(b) The temperature of the germinating piece: the higher the temperature, the greater the losses are.
(c) The composition of the air in the germinating piece: the more CO_2 in the piece, the more respiration and growth are suppressed.

(d) The character of the malt to be produced: losses rise with increasing levels of modification and longer germination periods.

Dark malts are always associated with greater malting losses than light malts.

Several options exist for lessening the effects of the various factors attributing to malting losses.

1.7.2.1 Limiting the Germination Period *Limiting the germination period*: rather than allowing the malt to undergo the entire germination process, it is interrupted before modification is complete. The resultant "chit" malt can be produced with a variety of methods. By doing so, malting losses decline by 2–5%, depending on the length of the germination period. The less time the grain spends in germination, the more of its original barley character it retains. Chit malt is essentially a barley adjunct and should therefore only comprise 10–15% of the grain bill. Special mashing procedures are necessary when utilizing chit malt in the brewhouse. This kind of malt can improve the foam characteristics of a beer, but results vary. Success is not guaranteed and is dependent on a number of factors. Moreover, there is a trade-off in terms of the negative impact on the flavor and flavor stability of the beer.

1.7.2.2 The Role of Carbon Dioxide in the Germinating Grain The *role of carbon dioxide in the germinating grain*. The growth of the kernel is restricted because respiration is restricted. Depending on the length of time the piece is exposed to CO_2 and the concentration in the air, malting losses can be reduced by 1–2.5%, but in the case of the latter, only in systems that employ CO_2 rests as part of the malting regime. Malt produced in this manner has a lower enzymatic capacity and modification is less advanced compared to ordinary malt.

1.7.2.3 The Resteeping Method The *resteeping method* truly cuts malting losses without undermining the quality of the malt. Consistent implementation of the resteeping process reduces malting losses by 1–1.5%, primarily through the inactivation of rootlet growth. However, respiration is also restricted (to 4–4.5%), making it possible to achieve low values for malting losses of approximately 5–6%. A variation on this method, resteeping in warm water (30–40 °C), can provide additional savings. This method was developed in the United Kingdom and requires the addition of gibberellic acid.

1.7.2.4 Germination Regime with Falling Temperatures A *germination regime with falling temperatures*, e.g., from 17 to 12 °C, can also lower malting losses. Since the grain exhibits strong growth when liquor is added, additions at defined intervals allow growth to be regulated more readily. The total malting losses can be reduced by 1–1.5%, compared to conventional malting methods with no detrimental effects on quality. Nevertheless, the electrical consumption of a refrigeration unit must also be factored in when calculating the profitability of this technique.

1.7.2.5 Using Auxins and Growth Inhibitors The *application of auxins and growth inhibitors* (prohibited in Germany). The addition of gibberellin hardly reduces malting losses, even given a shorter germination period. However, growth inhibitors, such as potassium bromate, result in substantially lower losses (refer to Section 1.5.3.9). Exposure to formaldehyde or steeping in a dilute solution of sulfuric acid also produces a similar effect. Certain starter cultures (refer to Section 1.5.3.8) can reduce the growth of the rootlets by approximately 50%. Starter cultures are allowed in Germany as long as the microorganisms were originally present on the barley.

Although there are numerous options listed here for minimizing the losses due to respiration and germination, it must be noted that adopting extreme measures to reduce malting losses has a negative impact on the quality of the malt. A minimum amount of starch in the kernel is required in order to control the malting process and thus to achieve the desired level of malt quality.

1.7.3 Calculating Malting Losses

The most precise method for determining malting losses is to weigh the quantity of barley at the onset of steeping and the cleaned, finished malt using automatic scales. The thousand kernel weights of barley and malt provide an approximation of malting losses. By contrast, the hectoliter weight is problematic; it delivers inaccurate results because the volumetric ratios change as the barley is converted to malt. The moisture content and the malting losses can be precisely determined from individual factors. All the remaining data are used in the calculation. The losses should be determined for each germination box or individual piece, as this yields a more accurate picture with regard to malting techniques or other operational variations.

Malting losses can be calculated according to the following equations:

Malting losses, (air-dried) = (B − M) ÷ B × 100

(B = quantity of steeped barley,
M = deculmed, kilned malt)

Malting losses, (dry matter)
= 100 − M (d.m.) × 100 ÷ B (d.m.)

(M (d.m.) = malt dry matter
= M × (100 − moisture content of the malt),
B (d.m.) = barley dry matter = B × (100 − moisture content of the barley)).

1.8 The Properties of Malt

It is important to precisely understand the properties of malt in order to further process it into beer. Malt is assessed according to its external characteristics and a number of mechanical and physico-chemical analyses.

1.8.1 External Characteristics

These characteristics are determined as follows.

1.8.1.1 The Degree of Purity of the Malt The *degree of purity of the malt* is evaluated according to the rootlets remaining on the kernels, the quantity of extraneous seeds, foreign cereals, dust, broken and damaged kernels, and the number of kernels exhibiting mold growth (also refer to color described later in this section). Further characteristics indicative of impurity include kernels that are bent in a beak-like fashion or even ungerminated kernels.

1.8.1.2 The Color of the Malt It should be yellowish and pure; steep liquor containing iron imparts a dull, gray color to the malt. "Striped" malt indicates that sulfurous fuel was employed during withering and curing in the kiln, while malt contaminated with mold is mottled with green, black, or red spots. A distinction is made between "non-relevant" and "relevant" red kernels. The latter should not exceed 1.5% of the malt; otherwise, the threat of gushing in the finished beer is elevated (refer to Section 7.6.8).

1.8.1.3 Aroma and Flavor of the Malt According to the type of malt, the aroma and flavor should be neutral to fragrant, not musty, sour, or burnt. Malt that smells or tastes moldy or rotten should be rejected. The same is true for smoky malt. These flavor notes can be detected by simply placing the *kernels* in one's mouth *without chewing them*. The hot water test is even more reliable for detecting such flavors.

1.8.2 Mechanical Analysis

These comprise hectoliter weight, thousand kernel weight, the sieving test, friability, and acrospire development.

1.8.2.1 Hectoliter Weight The *hectoliter weight* provides insight into volumetric relationships in the malt. However, it does not provide any information regarding losses during malting. The hectoliter weight of the barley prior to malting also cannot be estimated using this measure. The hectoliter weight varies between 47 and 60 kg. Well-modified, properly withered and kilned malt should possess a hectoliter weight between 48 and 55 kg. More precisely, the volume of the malt can be determined by its density, which normally ranges from 1.08–1.20 g/cm^3. Good malt, however, should not exhibit a density that exceeds 1.12 g/cm^3. Intense polishing, losses of the husks, and friction during transport increase both the hectoliter weight and the density. It is important to note that the latter can only be reliably measured in freshly kilned and deculmed malt.

1.8.2.2 Thousand Kernel Weight The *thousand kernel weight* of the malt provides an overview of the losses that occurred during the malting process. The malt (dry matter) is measured, and the calculation should yield a value between 25 and 35 g. Dark malts possess a lower thousand kernel weight than malts that are lighter in color.

Sieving measures the uniformity of the malt, specifically with regard to the size of the kernels.

1.8.2.3 Friability – Longitudinally Sectioning Kernels The *friability* of malt cannot be sufficiently measured by sectioning the kernels transversely with a grain cutter. Sectioning kernels longitudinally is an objectively accurate yet laborious method for gaining insight into the friability of malt kernels in addition to their partial and complete glassiness. The quantity of completely glassy kernels represents the kernels that did not germinate, and it should not exceed 2%. The friability of light-colored malt should be above 95%.

1.8.2.4 Friability – More Practical Analyses *The friability of the malt* can be evaluated with the sinker test (<10% is very good) and with the friabilimeter analysis according to Chapon.

Well-modified malt should exhibit 80% friable kernels, with the proportion of completely glassy kernels being less than 2%. The semi-glassy portion is further differentiated by repeated sorting over the 2.2 mm sieve. The modification "M" (>85%) and homogeneity "H" (>75%) are measured by staining the kernels with calcofluor according to the Carlsberg analysis method. Staining with methylene blue produces similar values with regard to modification.

NIR spectroscopy enables single kernel analysis of the homogeneity of barley and malt. It is possible to measure large sample volumes as whole grains (approx. 1000). The reproducibility is high, and the analysis can be automated. At over 0.92, the correlation is high between the data collected through measurement with NIR and predictions of homogeneity. This is also the case with protein and β-glucan.

1.8.2.5 Acrospire Development *Acrospire development* also provides a means for gauging the uniformity of malt. Furthermore, information about non-germinated kernels and huzzars can be obtained.

The generally accepted view is that the mean acrospire length for light malts should be 0.75 and no longer than 0.8 for modern dark malts. The length of individual acrospires is measured and grouped according to size; the size distribution data are then used to assess the uniformity of germination. Germination is considered uniform, if the proportion of kernels within the ranges of ½ to ¾ and ¾ to 1 is >84%. A higher proportion of grains with ¼ to ½ indicates late-germinating grains of a non-uniform piece. Along with acrospires that are only 0 to ¼ the length of the kernel, huzzars or bolters are usually present as well.

1.8.3 Physico-Chemical Analysis

This includes moisture content, laboratory yield according to the Congress analysis with finely or also with coarsely ground malt, the depth of color, the time required for saccharification, and other data as well. These serve to determine the degree of modification and can be used to draw conclusions about the malt and the potential it offers for downstream processing.

1.8.3.1 Moisture Content The *moisture content* of freshly kilned light malts is between 3.5% and 4.2%, while for dark malts, this value is lower, between 2.0% and 3.0%. During storage, the moisture content increases by 0.5–1%, and in commercial malts should not exceed 5%.

1.8.3.2 Moisture Content The *extract yield* varies between 72% and 79% for air-dried malt and between 77% and 83%, expressed as dry matter. The extract yield is usually above 80%.

1.8.3.3 Extract Difference For decades, the *extract difference* between finely and coarsely ground malt (FG/CG difference) served as a measure of the cytolytic modification as well as enzyme capacity of the malt. For well-modified malt ground with an EBC mill, the difference in the two was less than 1.8%; with a DLFU mill, it was below 1.4%. However, the reproducibility in comparing the two values was lacking across different laboratories, and the data was inconclusive for inhomogeneous malts. For these reasons, the analysis is no longer relied upon for the approval of newly cultivated barley varieties or as part of testing done to establish the equipment performance stipulated in warranties, e.g., inspections of new brewhouse equipment. This analysis remains relevant for assessing the cytolytic modification of malts created from cereals other than barley (refer to Section 1.9.1 ff.) because neither the friabilimeter value nor the staining methods are applicable.

1.8.3.4 Viscosity of the Congress Wort The *viscosity of the Congress wort* reveals the degree to which the substances providing structure and support in the endosperm have been degraded. This primarily concerns β-glucan in barley malt. The viscosity lies somewhere between 1.44 and 1.75 mPa·s; the viscosity is usually between 1.48 and 1.55 mPa·s in wort adjusted to an extract concentration of 8.6%. At a mash-in temperature of 45 °C, a certain amount of β-glucan degradation occurs in the Congress mash. Thus, compared to conventional brewing practice, the Congress mash delivers values for β-glucans that are too low (refer to Section 1.4.1.1). The 65 °C mash method provides useful data pertaining to the potential β-glucan content and the corresponding viscosity. As a rule, the viscosity of the 65 °C wort is 0.06–0.16 mPa·s higher than that of the Congress wort and can indicate that cytolysis in the malthouse was insufficient or inhomogeneous.

1.8.3.5 Determining β-Glucan Content The *determination of the β-glucan content* (according to Carlsberg) in the Congress wort and the 65 °C wort provides a clear indication of the cell-wall modification and the homogeneity of the degradation processes. The β-glucan content in the Congress wort should be less than 200 mg/l and below 350 mg/l in the 65 °C wort.

1.8.3.6 Time Required for Saccharification The *time required for saccharification* should be 10–15 min for light malts and 15–30 min for dark malts in which the enzymes have not been denatured. In addition, the *odor of the mash* is evaluated at this time.

The Congress mash is very dilute (1 : 6), and for this reason, the time required for saccharification is much shorter in the laboratory than it is in the brewhouse. Therefore, this analysis only provides relevant information if a significant error has been made in the production of the malt.

1.8.3.7 Color and Appearance of the Malt The *depth of color* of the laboratory wort is expressed in EBC units: For light malt, the color should be 2.5–4 EBC, for medium-colored ("Vienna") malt, 5–8 EBC, and for dark malt ("Munich"), 9.5–21 EBC. A more precise indicator for the ultimate color of beer is provided by the *color of the boiled Congress wort*. The color of the Congress wort produced using Pilsner malt should be no higher than 3.3 EBC, while the boiled wort color should be less than 5.2 EBC.

1.8.3.8 Appearance of the Wort The *appearance of the wort* and the time required for it to run off are also recorded. Wort with a low level of turbidity that runs off rapidly is considered desirable.

1.8.3.9 Apparent Limit of Attenuation The *apparent limit of attenuation* for the Congress wort should, at the minimum, be above 80%. German barley varieties intensely selected through breeding to produce brewing malt usually meet this requirement. Since there is no "maltose rest" at 62 °C in the Congress mash method, the limit of attenuation is usually lower than it is in the brewery.

1.8.3.10 Gelatinization Temperature The *gelatinization temperature* of the malt starch, determined by means of a rotational viscometer, lies between 58 and 66 °C. Gelatinization influences starch conversion during mashing with regard to the time required for saccharification, the limit of attenuation, and the spectrum of sugars in the wort. The gelatinization temperature is determined by the variety, provenance, and crop year. It is higher in barley cultivated under hot, dry growing conditions (e.g., during the dough development stage in the kernel).

1.8.3.11 Protein Profile The protein content of the malt lies somewhere between 0.1% and 0.3% (up to 0.5%) below that of the barley. It should not exceed 10.5% for extremely pale Pilsner and export beers. Pale lager and rich straw-colored export beers or specialty beers can tolerate a protein content as high as 11.0%. Munich-style *Dunkles* and similar beers should be brewed from malt with a protein content close to 12% to bring out their full-bodied and aromatic characteristics. The Kolbach index, expressed as a ratio of soluble nitrogen to total nitrogen, provides insight into the degree of protein modification. Values of 38–42% are considered favorable for malt with a protein content of 10.5%. Since the low molecular weight nitrogen has been consumed to produce melanoidins, the ratio will be lower in darker malts, placing it in the range of 37–40%. Because the Kolbach index can vary dramatically at times with the protein content of the barley, the soluble nitrogen content of the barley per 100 g (d.m.) is often provided along with the Kolbach index. Normally, the value for soluble nitrogen varies between 640 and 700 mg; however, in more protein-rich malts, a higher value may be permissible to secure a more favorable distribution of the nitrogen fractions in the malt (refer to Section 1.4.1.2). Among these fractions, *free amino nitrogen* (FAN) should constitute over 20% of the soluble nitrogen.

1.8.3.12 The Hartong–Kretschmer Four-mash Method The Hartong–Kretschmer *four-mash method* (isothermal) has seen widespread use. It offers assessment criteria for the compounds in the malt that will determine the soluble extract, the diastatic power of the malt, and the friability. The standard values for satisfactorily modified malts are as follows: VZ 20 °C = 24%, VZ 45 °C = 36%, VZ 65 °C = 98.7%, and VZ 80 °C = 93.7%. This results in a conversion number of 5.0. Higher demands on malt modification lend credence to the fact that a VZ 45 °C of approximately 38% is preferable. In addition, the VZ 80 °C is usually above 95% with modern single-floor kilns. The VZ 45 °C has diminished in relevance since 2005. For modern, highly modified and enzyme-rich varieties, the VZ 45 °C mash can no longer provide clear evidence of the relationships that reflect the modification attributes in malt.

1.8.3.13 pH of the Congress Wort The *pH of the Congress wort* is normally around 5.9. Depending on their color, darker malts exhibit a pH of approximately 5.7. The combustion of sulfurous fuels to carry out the withering and curing processes in the kiln lowers the pH by approximately 0.15. In this case, values for the extract content, Kolbach index, and the VZ

45 °C are higher. The titration acidity of the Congress wort in the first titration step (to a pH of 7.07) is usually 3.8–4.2 ml, and in the second step (to a pH of 9.0), 10.5–13 ml. The total acidity normally requires between 14.3 and 17.2 ml of 1 N NaOH.

1.8.3.14 The Stability of Kilned Malt Neither the germinative capacity nor *post-kiln heating* of malt (5 h at 86 °C) is the reliable method for determining the *stability of kilned malt*. Likewise, the *color of the boiled Congress wort* cannot serve as an indicator either, although it is a means of orientation regarding the color of the finished beer. The increase in color during the boil is dependent on the variety and provenance of the barley, the malting process, and the curing temperature (refer to Section 1.6.1.2). The higher the curing temperature was, the darker the color will be of the finished beer. Light malts can possess a color between 1.5 and 3.5 EBC. Standard values fall within a narrower range: 2.5–3.0 EBC. Although possible, in actuality, a malt color of 1.5–2.0 EBC is too light. For example, even very light Pilsner beer (approximately 6.5 EBC) brewed in Germany is produced using malt with a color of 2.5–3.0 EBC. A very good indicator is the dimethyl sulfide precursor content, which is ordinarily 5–7 ppm but is dependent on the conditions during wort boiling.

The thiobarbituric acid index (TBI) provides insight into color formation. Laboratory extracts produced from samples of properly withered and cured light malts exhibit values of 9–12, while the TBI of the Congress wort is slightly higher, at 13–15.

1.8.3.15 Supplementary Analyses *Supplementary analyses* include methods for the direct determination of enzymes (diastatic power 220–290 °DK and α-Amylase 30–60 ASBC) as well as further microbiological, chromatographic, and spectrophotometric analyses.

The iodine value for laboratory spent grain provides a glimpse into the degree of starch degradation in the Congress mash. Then again, since the impact of the two amylases on the starch granules depends on the degree of malt modification, the iodine value of finely and coarsely ground malt serves as an indicator for the degree and homogeneity of modification. Finely ground, well-modified malts possess values between 1.8 and 2.5, while for coarsely ground malt, the values are 6–8.9. Finely and coarsely ground malts with a medium level of modification exhibit values of 2.6–4.0 and 9.0–14.5, respectively. For finely and coarsely ground, poorly modified malts, the values are 4.1–4.8 and 14.6–17.5, respectively.

The analysis of environmentally relevant substances includes nitrosodimethylamine (NDMA), which should not exceed the "technical" value of 2.5 ppb.

The detection and measurement of volatile phenols in water vapor is used to identify and assess smoked malt. A smoked flavor is not desirable in standard light and dark malts. A smoked flavor is not perceptible if the concentration of volatile phenols remains below 0.2 mg/kg. With every malt delivery, each lot of malt should be subjected to a taste test (not chewed) to determine if any off-flavors are present (refer to Section 1.8.1.3).

A test for determining the *gushing tendency* of a barley or a malt sample can be performed. Unfermented but highly carbonated laboratory extract provides reliable information in this context. This test should be performed on malt samples exhibiting "relevant" red kernels (refer to Section 1.8.1.3). It may also be expedient to determine the concentrations of certain toxins for which maximum levels are prescribed.

Malt must possess attributes that facilitate processing and extraction in the brewhouse but above all produce wort that can be rapidly and consistently fermented. This will, in turn, ensure that the characteristics of the finished beer with regard to color, flavor, flavor stability, colloidal stability, and filterability fall within their desired ranges.

1.9 Malt from Other Grains

1.9.1 Wheat Malt

Wheat malt is produced according to the same guidelines as barley malt; however, certain aspects of the process require special attention due to the lack of husks.

1.9.1.1 Wheat Malted for Brewing Purposes *Wheat malted for brewing purposes* is not derived from special malting varieties because it comprises only 0.7% of the winter wheat harvest in Germany as a whole and just 3% of that in Bavaria. In fact, it has been demonstrated that winter wheat varieties exhibit a sufficient but not excessively high degree of modification and a lower susceptibility to contamination by microorganisms. Winter wheat is also less expensive than summer wheat. Generally speaking, winter wheat is less suitable for usage in the baking industry because of its (lower) protein content and thus is also not deemed economical

for use as animal feed. Over the years, a range of winter wheat varieties has emerged, which exhibit positive attributes making them suitable under the requisite climate and environmental conditions for malting and brewing applications. This varietal spectrum is also subject to the same changes as those impacting malting barley. The varieties best suited for malting and brewing can be found in the annual trade publications.

Analysis of malting wheat: it should possess a moisture content of 12–13% and a germinative capacity greater than 96%. Furthermore, the protein content should be less than 12%. The protein content of the malt used in the brewing industry is calculated by multiplying the nitrogen content by a factor of 6.25. By contrast, a factor of 5.7 is employed to determine the protein content in agriculture. Should a dispute arise, a reference to the nitrogen content can be used to settle it. In any case, for analysis purposes, the terms of reference include soluble nitrogen, nitrogen fractions, and free amino nitrogen. The kernels must be free of microbial contamination, particularly mold (evidenced by relevant red kernels and in some years red kernels in general). The same conditions that are applicable to barley in this regard also apply to wheat (refer to Section 1.1.3). The substances responsible for structure and support in wheat endosperm are characterized by a lower β-glucan content (0.5–2.0%) and a higher pentosan content (2–3%) compared to barley. This hinders degradation of the cell walls. A low oxidase concentration is important for obtaining wort and beer with a normal, pure color. The phenol number provides a rough orientation for the expected color.

1.9.1.2 Malting Procedures for Wheat *Malting procedures* for wheat: the first steep raises the moisture content to 30–32%, while an air rest of 12–20 h serves to reduce the water sensitivity. The second steeping sequence increases the moisture content to 37–39% and initiates uniform germination, which usually takes place in the germination unit. The target moisture content is approximately 44%. The germination temperatures lie mid-range at 14–15 °C. In order to increase the degree of friability, the temperature can be raised during the last 2 days of germination to 18 °C (or even up to 20 °C), if necessary. A higher moisture content (up to 47%) can be achieved through spraying when confronted with wheat that is difficult to modify and would otherwise possess an excessively high viscosity. If the grain is sprayed, the moisture content should not be allowed to exceed 38–39%. Wheat kernels are smaller than barley and therefore are more densely packed together in the bed. For this reason, the quantity of grain should be reduced by 20% in floor malting as well as in the germination box. This is not necessary for malting drums, transposal systems (*Wanderhaufen*), and Saladin germination systems with turning devices equipped with scoops (refer to Sections 1.5.2.2, 1.5.3.3, and 1.5.3.5). The acrospire begins its development under the testa, piercing it on the third day of germination, but continues to grow laterally along the kernel. Turning the piece too frequently can easily injure the germinating plantlet. This can disrupt the metabolic processes taking place inside the kernels, making them susceptible to contamination with mold. The changes in friability are more difficult to follow than with barley because the protein in the aleurone layer is stronger and more resistant to degradation. Compared to malting barley of the same provenance, wheat requires lower temperatures and less moisture, given the same time allotted for germination.

1.9.1.3 Kilning Wheat Malt *Kilning wheat malt* must be carried out more cautiously than barley malt, particularly in a multi-deck kiln. On a single-deck, high-performance kiln, the green malt is withered at 50–55–60–65 °C, although a further increase in temperature is to be expected once breakthrough is reached (exhaust air temperature of 45 °C). Once this has occurred, the kiln is heated to 77 °C over a 2 h period, followed by curing at 80 °C for another 2–3 h. Utilization of recirculated air should be approached cautiously with lighter malts in the kiln in order to prevent an undesirable increase in color. Losses incurred through the removal of the acrospire during cleaning the wheat malt are somewhat higher than with barley malt. This also results in a loss of protein of approximately 0.5–0.7%.

1.9.1.4 Wheat Malt Analyses *Analysis of wheat malt* is made somewhat more difficult by the removal of moisture, which is approximately 5% higher than that of barley malt. The extract content, calculated as dry matter, ranges from 83–87%, depending on the protein content. Ideally, the protein content should be close to 11.5%. Nevertheless, a protein content of 12–12.5% is acceptable for unfiltered Bavarian-style wheat beers, considering their characteristically high turbidity. Beers brewed in the filtered wheat beer style *Kristallweizen* benefit from a protein content of 11% or less. The loss of the acrospire determines the amount of soluble nitrogen present compared to the total nitrogen, usually in the range of 36–39%.

The value for VZ 45 °C also lies within this range. The nitrogen fractions in wheat malt are higher in coagulable nitrogen and nitrogen capable of precipitation with $MgSO_4$ (the latter approx. 40%) and contain less FAN (12–14%). The extract difference (fine/coarse-grind) is normally between 1.0% and 2.0%, making a more intensive mashing regime necessary (refer to Section 8.4.3.4). The wort color is 3.5–4.5 EBC, while that of the boiled wort is 5–6 EBC. The lower values for color are appropriate for *Kristallweizen* wheat beers. Wheat malts, which are medium to dark in color (10–20 EBC), are also employed, depending on the style of beer to be brewed. The concentration of DMS precursor is low in wheat malt, and it is not considered to be a limiting factor. The polyphenol content is also lower due to the missing husks. Ferulic acid is an important compound contributing to the typical wheat beer aroma and flavor. Its concentration in both wheat and barley malt is comparable. Hordenine, an amine and precursor of nitrosodimethylamine, is only present in small concentrations.

The limit of attenuation for wheat malt varies from 78% to 81%, and the diastatic power from 250 and 420 °WK. However, the α-amylase content is lower than comparable barley malts and amounts to 30–60 ASBC units, depending on the wheat variety and the crop year. Even lower α-amylase values can delay saccharification in the mash and produce the corresponding iodine reaction in wort and beer. The iodine reaction of the laboratory spent grain, and also those in the brewhouse, is higher than that observed with barley malts.

The "gushing test" is also carried with wheat malt produced with grain harvested in critical crop years. It is performed as follows: the concentration of oxalate, which may also play a role in the excessive foaming of beer, is approximately 50% higher in wheat malt than in a comparable barley malt.

The tendency for a sample of unmalted or malted wheat to foam excessively or gush can be assessed using carbonated extract. The extract is stored for 4–5 days and then tested to determine whether it will gush. The volume of beer that foams over from a 0.5 l bottle is measured as follows: a volume of 1–10 ml represents a "stable" beer, a volume of 11–30 ml indicates a beer that is "susceptible" to gushing, and any volume over 30 ml is considered an "unstable" beer with a strong propensity for gushing. However, one must understand that wheat has an oxalate concentration 50% higher than that of barley. The oxalate levels also depend on the grain's provenance and the crop year.

In addition to the measured values described above, it is important to mention that most who are involved in the processing of wheat calculate the nitrogen content using a factor of 5.7 rather than 6.25, as is common for barley or barley malt. This discrepancy between the two factors emerges repeatedly and can be avoided by referencing the nitrogen content of wheat or wheat malt, since otherwise only soluble nitrogen, the nitrogen fractions, and free amino nitrogen come under relevant discussion for the protein content.

1.9.2 Malt from Alternative Cereals

Other cereals capable of undergoing the malting process include rye, triticale, spelt, emmer, einkorn wheat, oats, Khorasan wheat (kamut), and tritordeum. These malts are utilized as baking agents or in other food production areas. They are likewise employed to brew beer (in Germany, only in the production of top-fermented beer). Rice and corn (maize) can also be malted if they exhibit the requisite germinative capacity. Malts produced using rice, corn (maize), and millet and also pseudocereals (e.g., amaranth, buckwheat, and quinoa) are not legally permitted for use as brewing grains in Germany.

1.9.2.1 Rye Winter rye is generally employed for malting. Rye only requires a short cultivation period, as it matures very rapidly. For this reason, it is also less susceptible to fungal infection or attack by animal pests. Rye exhibits a moderate dormancy. This makes it more prone to pre-germination on the plant before it can be harvested. As such, it is best to harvest rye earlier, immediately after it has reached maturity, e.g., with a moisture content of 18–20%, and subsequently dried. Rye intended for use in the brewing process should possess a protein content of 12% ($N \times 6.25$), while a content of 14% is nevertheless acceptable for the production of diastatic malt.

Even if rye is deemed ready for malting, it is somewhat more difficult to process due to its high concentrations of pentosans. This is best alleviated through a steeping regime performed as follows: the moisture content is increased in a stepwise manner to 30% and then 38%, followed by an additional step up to 43% in the germination box. A steeping and germination temperature of 15 °C allows for a total vegetative period of growth of 7 days. The germination temperature is raised to 18–20 °C for the last 24–36 h to aid in degradation of the kernels' cell walls. After the usual withering process, curing is typically carried out at temperatures of 80–85 °C.

The analysis of rye malt consists of the following: a moisture content of approximately 5%, an extract content (d.m.) of 85–88%, an extract difference (fine/coarse grist) of 1.5–2.0%, a viscosity of 3.8–4.4 mPa·s (!), a protein content of 10.5–12%, a Kolbach index of 45–55%, a value for VZ 45 °C (almost) as high, a limit of attenuation of 80–82%, a diastatic power of 300–500 °WK, a value for α-amylase of 50–100 ASBC, and a color of 6–20 EBC, depending on the type of malt.

1.9.2.2 Triticale This grain is a cross between wheat (*Triticum*) and rye (*Secale*) and was bred to combine the quality of the former with the favorable attributes of the latter, namely winter hardiness, ease of cultivation, and resistance to disease. Only the winter varieties are cultivated in temperate zones. Although triticale is better known as a fodder plant or for the production of bioethanol, it was used in the 1980s as malt and – where permitted – as an adjunct in brewing. Experience with this grain in brewing is still limited.

Triticale is somewhat richer in protein and is malted similar to barley, wheat, and rye through the use of a pneumatic steeping regime. The moisture content is increased to 30% and then to 38% in the steeping vessel and afterward raised to a maximum moisture content of 42–43% in the germination box. It is steeped and germinated at 15 °C over a period spanning approximately 7 days. In this case as well, the temperature can be raised to 18–20 °C during the last one-and-a-half to two days of germination. The withering and curing regime employed for wheat and rye should also be used for triticale. Similarly, the lack of husks creates a denser bed during germination and kilning. Therefore, it is recommended that the quantity of grain be reduced by 10–20% than is typical for malt production with barley.

The analysis of triticale malt reveals a moisture content of around 5% and an extract content of 84–87%. The extract content is dependent on the protein content, which lies within the range of 12.5% and 15%. A Kolbach index of 45–55% means that there is a large quantity of soluble nitrogen present in the kernel. The value obtained with the VZ 45 °C analysis is 4–10% less than the value for Kolbach index. The extract difference (fine/coarse grist) is 1.5–2.0%. The viscosity, at 1.9–2.3 mPa·s, is significantly lower than that of rye. Given the values for diastatic power (430–700 °WK) and for α-amylase (60–120 ASBC), the limit of attenuation can cover a broad range, generally between 74% and 82%. The color varies from 5–9 EBC, depending on how the malt is cured.

1.9.2.3 Spelt, Emmer, and Einkorn *Spelt, emmer, and einkorn* are all early wheat varieties. Each species has retained its husks, and during threshing, the husks are only partially removed. If these grains remain unhusked, they are collectively known as "vesen" and are used for sowing. However, if these grains are to be malted, they must be further processed in a type of mill capable of removing their husks. The hulling machine must be adjusted carefully to ensure that the embryo is not damaged or separated from the kernels. The protein content lies between 12% and 14%.

As previously described, malting is performed using a pneumatic steeping process with the moisture content increasing in a stepwise manner. The air rests are somewhat shorter, each lasting 10–12 h. After the grain has begun to uniformly chit in the germination box, the temperature is held at 17 °C, while the moisture content rises to 47%. Together, steeping and germination last 6 days. With this malting regime, the statistical data (refer to Section 1.9.5) report the most favorable extract values to be 83–84% and the limit of attenuation to be 80–82%. The α-amylase activity is only 18 ASBC, with a diastatic power of 360 °WK. Despite this, the time required for saccharification remains short in the Congress mash method. Pentosans are primarily targeted in the degradation of the cell walls. A viscosity of approximately 1.70 mPa·s can be attained under the germination conditions listed above. The Kolbach index is 43% at a protein content of 14.5%, while the proportion of FAN amounts to only 14%. The color reaches values of 3–6 EBC, depending on the degree of modification and the kilning regimen.

Emmer exhibits the same enzyme profile as wheat. A limit of attenuation of 80% can be achieved when brewing with emmer malt, which possesses a protein content of 12% and an extract content of 88%. Emmer, with a diastatic power of 350 °WK, has an α-amylase activity of only 27 ASBC. The Kolbach index is 42%, while the proportion of FAN in the soluble nitrogen is 13%. The viscosity is 1.70 mPa·s. The color of the Congress wort approaches that of wheat malt (3–6 EBC).

Einkorn kernels are smaller than those of other wheat varieties. Emmer malt produced according to the standard micromalting regime for barley (moisture content of germinating grain of 45%, 7 days of steeping, and germination at 14.5 °C) results in an extract content of 85% but a limit of attenuation of only 71%. This is the case in spite of values comparable with emmer for α-amylase and diastatic power and a saccharification time

of 10–15 min. The Kolbach index was 33% with a protein content of 14.5%, while the proportion of FAN was 15.7%. The viscosity, at 2.9 mPa·s, is relatively high. Better values can certainly be achieved through a more intense malting regimen. The color corresponds to that of wheat malt.

1.9.2.4 Oats *Oats* have largely been forgotten as a brewing grain in Central Europe. Their composition (higher levels of protein, β-glucan, and fat) makes them less suitable for malting and brewing applications. The composition of new varieties is more favorable, to the extent that oats have gained in importance as a raw material for specialty beers as well as functional beverages.

The slender form of oat kernels enables them to absorb water very quickly during steeping and germination. The strong husks form a bed of grain that is less dense. A brief period of steeping and an abbreviated air rest followed by a second careful addition of steep liquor in the germination box induce rapid growth in the kernels. The optimal malting regime is as follows: 8 days of steeping, germination, and growth at 46% moisture at a temperature of 17 °C.

The analysis data for the malt show an extract content of less than 75%, a limit of attenuation of 80.7%, and a protein content of 12.5%, with a Kolbach index of 38%. The viscosity of the Congress wort is quite favorable at 1.47 mPa·s. This value increases by 0.12 mPa·s in wort mashed isothermally at 65 °C. This is due to the substantial elevation in the initially low β-glucan content. The α-amylase activity is 24 ASBC, and the diastatic power 270 °WK, which results in saccharification in less than 10 min. The color is around 3.5 EBC units.

1.9.2.5 Millet a number of varieties of this small-grained cereal are grouped together as "millets." Of these, the pearl millet, foxtail millet, fonio, teff, and finger millet are of interest, since they play a role in malting and brewing in various parts of the world. Of these, proso millet will be discussed here.

The husks of millet are thick, and therefore, moisture uptake during steeping is slow. At a steeping and germination temperature of 22 °C and a moisture content of 44%, only 5 days is needed to achieve a normal degree of modification. Although the size of the individual kernels is only 2–3 mm, the normal decks in germination boxes and kilns may still be used, but the bed depth should be reduced by one-third.

The analysis data are as follows: the extract content is 64% (dry matter!), the viscosity is 1.53 mPa·s, and the limit of attenuation is 74%. The protein content is 11% (up to 13.5%), while the Kolbach index is 39%. FAN is normally 22%. The activity of both α- and β-amylase is low, but limit dextrinase activity is high. Millet does not contain gluten, which makes it suitable for production of beverages for those with celiac disease.

1.9.2.6 Sorghum *Sorghum* (millet) is, botanically speaking, more closely related to corn or sugar cane. It is more frequently used in brewing as an unmalted adjunct than as malt.

The enzyme profile of sorghum fluctuates greatly, depending on its provenance and variety. How the grain is stored, the length of time, and the temperature (12–23 °C) also play a role. Storage conditions may favor contamination of the grain with molds. Therefore, it should be regularly examined for the presence of mold. In countries outside of Germany, various disinfecting agents, such as sodium hydroxide and calcium hydroxide, are added in the steep, also in combination with gibberellic acid (0.02–0.2 ppm) and bromate (15–150 ppm), as described in Section 1.5.3.9. However, a consensus has not been reached on the efficacy of these measures.

Malting techniques for millet vary greatly. It is more or less empirical according to which varieties of millet are grown and their provenance. Short periods of steeping (2 × 5 h) are followed by an extended air rest of approximately 20 h. A moisture content of 44–48% during germination for 36 h at 25–28 °C results in favorable analysis values. The formation of amylases and proteases can be promoted by subjecting the grain to a final steep in warm water for 1.5–3 h before transfer to the germination box. In practice, a broad range of temperatures is encountered in the kilning process, between 45 and 100 °C. Malt for use in brewing is usually withered at 50 °C and then "cured."

The analytical data for sorghum malt covers a broad spectrum, varying according to provenance, variety, crop year, and malting technique. The following analyses are provided with values considered typical for sorghum: extract, dry matter (71–84%), viscosity (1.29–1.75 mPa·s), limit of attenuation (73–95%), color (2.2–15 EBC), protein content (7.5–12.5%), Kolbach index (20–38%), diastatic power (12–60 °WK), and α-amylase activity (12–60 DU). The DMS content is within the range of that for barley malt, despite the low curing temperature.

Sorghum that has been malted according to the standard micromalting regime for barley (7 days of steeping and germination at 14.5 °C, moisture content of 45%, and curing temperature of 80 °C) yielded the following values: extract (73.9%), viscosity (1.96 mPa·s), limit of attenuation (79.7%), protein content (7.8%), Kolbach index (34%), FAN (25% of soluble nitrogen), diastatic power (83 °WK), and α-amylase activity (8 ASBC). Sorghum does not contain gluten.

1.9.3 Pseudocereals

Amaranth, buckwheat, and quinoa are classified as pseudocereals. According to the tax laws governing beer production in Germany, pseudocereals are not permitted in the production of beverages classified as "beer," but they may be utilized in a variety of other beverages, including functional beverages. These grains are suitable for celiac disease sufferers because they do not contain gluten.

1.9.3.1 Amaranth *Amaranth* originated in the tropics. The kernels are very tiny; the thousand kernel weight is only 0.6 g. The malting process for amaranth should be carried out in floor maltings; otherwise, the perforated decks of a malting plant would have to be modified for each stage of the malting process, from the steep to the kiln. Moisture uptake is very rapid, and the depth of the bed is only 20% of the depth of germinating barley. After a thorough washing sequence, the germination temperature is approximately 30 °C. A regime of 8 days of steeping and germination at 8 °C and a moisture content of 54% has been shown to yield the best results.

After performing the standard micromalting regime used for barley (described above), the following analysis results were obtained for amaranth: malt extract: 79.7%; viscosity: 1.97 mPa·s; color 5.6 EBC; protein content: 15.2%; Kolbach index: 42%; and FAN expressed as% of soluble nitrogen: 18%. The diastatic power was only 88 °WK, while α-amylase was only present in traces. For this reason, saccharification was not achieved in the Congress wort, and the limit of attenuation only reached 22%.

1.9.3.2 Buckwheat *Buckwheat* originated at high elevations in the Central and Eastern Asian mountains. There, the growth period is very short (10–12 weeks). The malting process with buckwheat is characterized by extremely rapid moisture uptake; i.e., steeping is very short. Germination takes place at 20 °C, so that β-amylase can be maximized. Nevertheless, the development of α-amylase is so weak that exogenous enzymes must be added during mashing to ensure that the process proceeds normally.

After the standard micromalting regime for barley was used with buckwheat, the extract content was determined to be 52.9%, a very low value. The protein content was 15.4%, and the Kolbach index was 30%, while FAN comprised 15% of the soluble nitrogen. The viscosity was 3.50 mPa·s. The values for diastatic power and α-amylase were similar to those for amaranth, and saccharification did not occur in the Congress mash. The limit of attenuation only reached 46%. The wort color was very light at 2.5 EBC.

1.9.3.3 Quinoa Historically, *quinoa* comes from the Andes regions in Latin America, but it is also cultivated in North America and Europe. Originally, saponins were present in the quinoa seeds. These have no physiological benefit for humans and possess a bitter flavor. Due to selective breeding, quinoa is now available that is virtually free of saponins. Quinoa seeds are extremely small. The thousand kernel weight is only 1.85–4.2 g. Quinoa does not exhibit dormancy.

The seeds are peeled gently prior to malting to prevent injury to the embryo. Germination begins rapidly at 8 °C and undergoes intense growth for three to 4 days until the germination process ceases. The standard micromalting regime for barley yields an extract content of 83.2% and a normal viscosity of 1.52 mPa·s. However, due to the low diastatic power and slight traces of α-amylase, a normal iodine value is not achieved in the wort, and the limit of attenuation only reaches 63.5%. The protein content is 13.7%, with a Kolbach index of 40% and a FAN content of 23% of the soluble nitrogen. Utilization of this malt for brewing also requires the addition of exogenous enzymes in the brewhouse.

1.9.4 Specialty Malts

These kinds of malts are added in certain percentages to the normal grain bill in order to enhance the profile of the beer, e.g., in terms of color, flavor, body, foam characteristics, acidity levels, and overall stability. Specialty malts include roasted malt, caramel malt, melanoidin malt, chit malt, and acidulated malt (acid malt).

1.9.4.1 Roasted Malt *Roasted malt* is employed to impart a specific hue to beer, bringing about a darker or deeper color. Even when brewing

beer with dark malt, sometime the desired depth of color cannot be achieved simply with dark (Munich) malt alone. It is recommended that roasted malt only be added at a rate of 1–2%.

Roasted malt is produced by moistening light-colored malt and carefully heating it in a drum roaster to temperatures above 200 °C (up to 220 °C). The malt is roasted in the drum under constant rotation. Initially, the formation of melanoidins is strong, and the moisture content drops to 1–2%. The starch undergoes depolymerization, and proteins are denatured and partially degraded to low molecular weight compounds. As the reactions continue, dark, bitter roasted products (assamars) are formed. Their quantity can be held to within certain limits if the malt is moist instead of dry. To remove the charred and bitter substances, the malt can either be roasted in a vacuum atmosphere, or moisture can be sprayed into the roaster prior to the end of the roasting process, since these substances are volatile in steam. Roasting is halted by emptying the contents of the drum onto flat, perforated decks. There, the malt is cooled and homogenized by stirring it while still on the flat surface of the deck. The enzymes are completely destroyed during the roasting process. The endosperm of roasted malt should be uniformly friable and exhibit a dark brown color similar to that of coffee. Furthermore, the endosperm should not be shiny, but the husks might be.

A relatively new practice is the use of naked barley to make roasted malt, which avoids the introduction of the bitter substances from the husks. However, producing roasted malt from naked barley has not become as widespread as doing so from dehusked malt, which also contains fewer roasted aroma compounds. Wheat malt lends itself quite favorably to roasting (in Germany, only allowed in top-fermented beer styles; the same is true of roasted and caramel malts produced from rye or other cereals). Roasted barley malt is classified into three categories based on the intensity of its color: approximately 800, 1000–1200, and 1300–1400 EBC units. Roasted malt made from wheat, rye, and spelt are also classified in this way, but their color is somewhat lighter than that of roasted barley malt.

The amount of color that roasted malt can impart to beer varies according to the method of production and can range from 1300–1600 EBC. The extract yield (dry matter) is only 60–65%.

In this context, *Röstmalzbier* (literally "roasted malt beer," a coloring agent that conforms to the requirements of the *Reinheitsgebot*) is added to wort and beer to adjust the color as needed. *Röstmalzbier* is made from 60% Pilsner malt and 40% roasted malt with a high hop addition. The wort is fermented and sold at a gravity of 16–20%. Its color is around 8000 EBC. The extract content as well as the color can be increased even further through vacuum evaporation. The vacuum atmosphere also aids in the removal of burnt aromas and gives the *Röstmalzbier* a more neutral character. The extract content after vacuum treatment is 30–32%, and the color is approximately 12,000 EBC.

1.9.4.2 Caramel Malt This malt can be added at a rate of 3–5% to enhance the full-bodied, malty character of beer. Larger additions of up to 10% of the grain bill are possible for some beer styles. Caramel malt is produced from green or kilned malt. The malt is steeped until it possesses a moisture content of 40–44% and is placed in a roasting drum where the contents of the kernels are liquified and saccharified within 3 h at a temperature of 60–75 °C. During this period, an abundant quantity of soluble nitrogen is created, and the acidity increases. Subsequently, the temperature is raised to 120–180 °C.

The typical caramel substances are generated during this phase of the process. By venting the exhaust air, many aroma compounds, such as Strecker aldehydes and furfural, as well as heterocyclic compounds are vaporized and thus eliminated. For example, dark caramel malts, which are calculated to possess the same color as dark Munich malt, also exhibit much lower concentrations of these compounds. This is of great importance in terms of flavor and flavor stability when utilizing these malts in the production of lighter-colored beers.

The enzymes are denatured at these high temperatures, and the proteins are completely altered.

Light caramel malt can be divided into two categories by color: 20–30 EBC and 30–40 EBC. The kernels are still soft, and their moisture content, especially for malt lighter in color, is around 2–3% higher than it was previously. The extract content is approximately 1.2–1.6% lower than malt produced from the same barley, due to the losses incurred as a result of the roasting process. The Kolbach index declines by 7–8%, bringing it to around 32%. The viscosity of the Congress wort is 0.1 mPa·s higher, whereas the pH drops by 0.5, which is confirmed by the increase in titratable acidity.

Dark caramel malt is held at the roasting temperature for a correspondingly longer period. Dark caramel malt is grouped into three different categories on the basis of color: 80–100, 110–130, and

140–160 EBC. The extract losses are 2% higher, i.e., at 3.2–3.6% overall. The pH value is 5.3, while other values vary only slightly compared to those for light caramel malt.

An intermediate stage in the production of caramel malt yields a product with a color of 35–50 EBC. This lends a reddish hue to the wort and beer.

"Aroma malts" exhibit colors equal to approximately 250 EBC. They contribute an intense malty aroma to dark beer and specialty beers.

In order to utilize the roasting drum more efficiently, the ventilation of the green malt is halted on the last day of germination. This allows the temperature to rise to 40–50 °C (refer to stewed malt), which causes the formation of low molecular weight degradation products, enabling a "saccharification rest" to be carried out at 70 °C within a mere 1–1½ h in the roasting drum. The caramelization process for aroma malt occurs in a manner similar to that for other caramel malts.

Extremely light caramel malt (only 3.5–6 EBC) is held for 45–60 min in a roasting apparatus at 60–80 °C. This liquifies the contents of the kernels. The malt is subsequently dried in a kiln at 55–60 °C.

Roasted malt and caramel malt can also be made from wheat, rye, and other cereals. The malting industry is very innovative, so brewers should consult specialty malt producers for the most current information on the range of products available.

Roasted malt and caramel malt are also available as liquid malt extract or in dry form as a spray-dried or granulated product. In addition, "caramel malt beer" (like roasted malt beer) is also produced.

One production technique involves processing dehusked caramel malt or coloring malt (generally known as roasted malt today). The malt is finely milled and formed into granules. Granulation reduces the hygroscopic properties of the "malt powder," so that during production it neither generates dust nor hardens into clumps. Granulated malt extract can be added to the wort kettle, where it dissolves quickly. The malt extract is available in different colors, 30, 100, 300, and 1000 EBC, depending on the application.

The extract can also be used to make wort. In this case, a mash filter is usually employed for separation since it enables higher-gravity wort to be produced. This wort extract is then flash pasteurized or treated by means of ultra-high-temperature pasteurization in order to sterilize it. The sterile extract is subjected to vacuum treatment to reach the final extract concentration. This can be added to the wort at the end of the boil or at another point on the hot side of the brewing process.

If the production process from the mash filter comprises wort boiling, fermentation, clarification, evaporation, and aseptic packaging, then the extract can be added immediately upstream from the beer filter. Here, it serves a similar function to that of *Röstmalzbier*, namely as a means for correcting the color and to increase the body and the character of the beer in general. Anyone wishing to use these products must first establish whether they are permitted in their respective country or region.

1.9.4.3 Melanoidin Malt *Melanoidin malt* is derived from earlier "stewed malts," but in contrast to those of the past, modern germination equipment allows much more precise control over the process conditions. In the past, "stewed malts" were produced in floor maltings. The green malt set aside for the production of dark (Munich) malt was couched in a separate heap about 50 cm deep approximately 36 h prior to the end of the germination period. The layer was allowed to warm up on its own and was sometimes covered with wooden planks or tarpaulin in an effort to retain the heat in the couched grain. Temperatures of 40–50 °C were reached but did not rise above this level due to the increased concentration of CO_2 in the grain. This stage of development was characterized by a heavy accumulation of degradation products in the barley kernels. However, these degradation products accumulated because growth ceased, and they were therefore not utilized in respiration or other metabolic processes. The sugars (invert sugar), amino acids, smaller peptides, and organic acids led to an abundance of Maillard products during withering and curing in the kiln. The resultant compounds exhibit strong reducing properties (hence, the former designation as *rH-Malz* ("rH malt") in Germany). Relatively low curing temperatures of 70–85 °C are sufficient to attain a malt color of 40–60 EBC units in malt produced in this manner. Saccharification in the Congress mash lasts 15–20 min, while the extract content is around 1–1.5% lower than dark (Munich) malt; the pH was also 0.1–0.15 lower (depending on the color of the malt). Despite adherence to a similar malting regime, conditions differ between the germination box system and floor malting since the carbon dioxide does not remain in the germinating grain but instead migrates into the plenum under the deck of the box. This pulls fresh air from above the grain into the piece. Of course, the layer of CO_2 builds up more quickly in germination boxes of an older design with a less-spacious plenum below

the deck than in larger units that feature a plenum that is approximately 2 m in height.

The addition of around 5% melanoidin malt can provide a deeper color and enhance the character of lighter beers. It may also be used in place of dark malt at a rate of up to 35% when brewing dark beer, specialty beers, or *Märzen*-style beers.

In the past, floor malting was constantly beset with problems associated with uninhibited metabolic reactions and their accompanying influence on flavor and microbiological stability. These problems are no longer encountered with pneumatic malting systems, provided they are operated correctly.

1.9.4.4 Chit Malt *Chit malt* can be added to the grain bill at a rate of 10–15% in an effort to compensate for overly modified malt or to improve foam formation and head retention. Chit malt is produced from kernels that have begun to "chit," meaning that the rootlets have begun to appear. This can even be observed in steeping grain if the proper malting regime is followed (refer to Section 1.3.6.2). Variations on (kilned) chit malt include flaked barley malt and green malt at a corresponding stage of growth.

Green malt spoils within a very short period of time and therefore must be processed immediately upon removal from the germination vessel. Therefore, the use of chit malt is limited to those breweries that have their own malthouse. Usage of green malt does not conform to the stipulations in the tax law governing beer production in Germany, which state that in order to be considered malt, the germinated grain must be kilned.

Chit malt is allowed to sprout or "chit" uniformly for 2 days or for half the time usually devoted to steeping and germination. It can be added in higher proportions to the grain bill, but wort clarification in lauter tuns and filterability of the beer should be closely monitored.

1.9.4.5 Acidulated or Acid Malt *Acidulated or acid malt* improves the mash pH when added to the grain bill at a rate of 2–10%. The addition primarily affects the pH of the wort, but it does have some influence on the pH of the beer. The lactic acid in acidulated malt is what brings about this effect. Lactic acid is formed by the lactic acid bacteria present on the malt. Steeping the malt and then holding it at a temperature of 45–48 °C for a period of 24 h provides optimal conditions for the bacteria to produce the acid. The "mother solution" can be recovered for reuse in acidifying further batches of malt. The acidulated malt is carefully dried and kilned to retain the target color of less than 6 EBC.

Acidulated malt can also be made by sprinkling green malt with a solution of lactic acid obtained from natural lactic acid production. As described above, natural lactic acid is produced according to a specially approved procedure, e.g., by inoculation of first wort with these bacteria at temperature of 47 °C (refer to Section 2.1.3.15).

The pH of an aqueous extract with a lactic acid concentration of 2–4% is approximately 3.8. This aqueous extract is beneficial when added to wort in the kettle during boiling (refer to Section 2.5.3).

1.9.5 Micromalting

Micromalting allows small quantities (50–1000 g) of barley or other cereals to be malted under defined germination conditions (moisture content, temperature, and time). The behavior of the grain can be observed during the germination process. Simple malt analyses, standard analyses, or special analyses may be performed on the malt, depending on the quantity of malt produced. Furthermore, this malt can be used in pilot breweries to conduct smaller-scale brewing trials.

Micromalting can be employed to accomplish the following, as exemplified with malting barley:

(a) to assess the brewing quality of newly developed barley varieties;
(b) for (early) testing of the malting behavior and the malt characteristics of a new crop year;
(c) to determine the suitability for malting and the malt quality of lesser known varieties and imported barley;
(d) to develop optimal malting methods/regimes for a, b, and c; and
(e) to monitor the progress of malting in practice over the entire process or in various stages of the process.

The original micromalting batch production method in the *Weihenstephaner Klimakammer* (Weihenstephan climate-controlled chamber) as it is described in MEBAK is still relevant today – with a few minor corrections:

Steeping: 5 h wet, 19 h dry, 4 h wet, 20 h dry, and 2 h wet; after a total of 72 h has passed, adjust the moisture content in the grain to 45% at an air temperature of 14 °C and a humidity of 95%; the temperature of the germinating grain is 14.5 °C, with a total steeping and germination period of 144 h. The moisture content of the green malt must be 45–45.5%.

Withering for 16 h at 50 °C (the moisture content should remain below 10%); the temperature

is increased to 80 °C in 2 h; curing at 80 °C for 3 h or until the final moisture content of 4.0 ± 0.5% is reached.

The standard micromalting regime can be used for other kinds of cereals (refer to Section 1.9). Nevertheless, in some instances, it may be necessary to carry out the "statistical malting regime" with three different moisture levels, germination temperatures, and germination periods, while also applying a constant withering and curing process in order to determine the best parameters for malting. Only then will it be possible to generate the best attributes for a specific type of malt which are able to meet the requirements for its respective application (e.g., brewing malt, diastatic malt, and as an ingredient in foods).