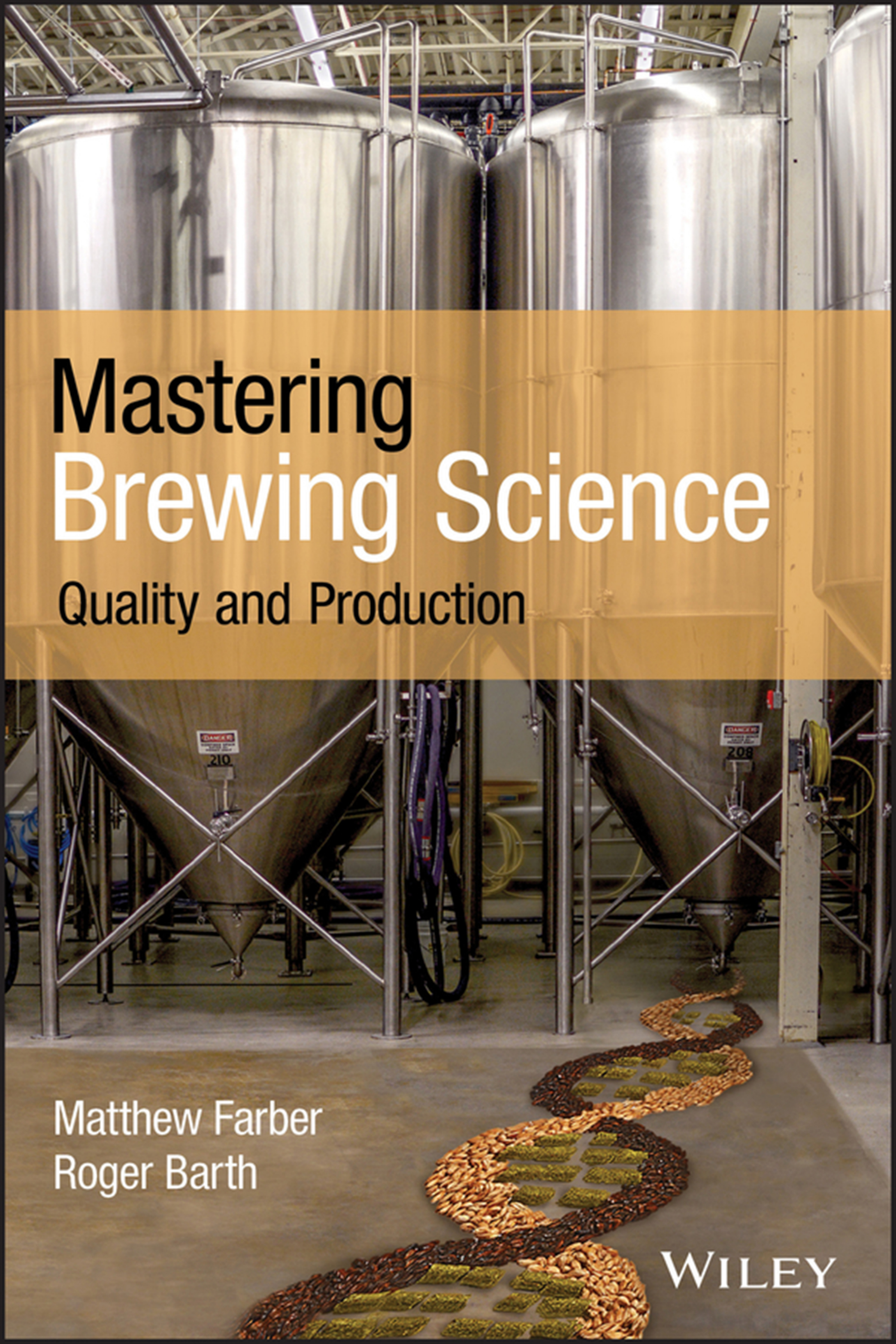

Mastering Brewing Science

Quality and Production

Matthew Farber

Roger Barth

WILEY

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Matthew Farber, PhD, is the program director of the Brewing Science Certificate program at the University of the Sciences in Philadelphia where he is also an assistant professor of biology. He received a BS in Biology with a minor in writing from Seton Hall University and a doctorate in molecular and cellular biology with a minor in teaching from the University of Pittsburgh. His research focuses on innovative applications of biotechnology for the improvement of beer production, and he is an inventor on two pending patents in brewing. He is an active member of the American Society of Brewing Chemists, the Master Brewers Association of the Americas, and the Brewers Association.

Roger Barth, PhD, has been a faculty member in the chemistry department at West Chester University in Pennsylvania since 1985. He created a course entitled The Chemistry of Beer and is the author of its textbook. Barth's research interests center upon brewhouse processing and beer and malt analytical methods. He has a BA in Chemistry from La Salle College. His doctorate is in physical chemistry from The Johns Hopkins University, and he has done postdoctoral work in the area of catalysis at University of Delaware and Drexel University. He is a member of the American Chemical Society, the American Association for the Advancement of Science, Sigma Xi, the American Society of Brewing Chemists, and the Master Brewers Association of the Americas.

PREFACE

Brewing is a creative art. Underlying that art is a framework of technical knowledge, mostly in chemistry and biology, but with significant contributions from physics and engineering. To make five gallons of drinkable beer requires little scientific background, with the definition of *drinkable* up for debate. To make hundreds of batches of beer, each of which meets the expectations of the customers, each of which is consistent with the last, sound science is required. This is the goal of modern brewers.

This book is written as an instructional resource for teaching or learning brewing practice and theory with a focus on the underlying science. We try to strike a balance between critical scientific concepts, beer production, and day-to-day practical issues in beer quality. By understanding the science of beer production, readers will be better equipped to troubleshoot problems in the brewery, one of the most critical skills for a successful career in beer. We have produced hundreds of illustrations to demonstrate key concepts and to demonstrate the numerous pieces of equipment commonly used in breweries. Unlike drawings provided by equipment suppliers, our drawings do not inform operation or maintenance. Rather, they illustrate essential design elements and concepts as they pertain to the process.

In this book, we first introduce a high-level view of the brewing process. Then we dive into the fundamentals of biology and chemistry with appropriate application to the brewing process. These concepts will be critical to better understanding of subsequent chapters. The remaining material is presented in order, from raw materials, through the brewing process, and on to methods for quality. All employees at a brewery should be trained in basic concepts of quality. Quality is best managed at the source where response time is quick.

As more and more brands line the shelves, the consumer has more and more options. If one batch of beer is flawed in the eyes (and palate) of the consumer, it is easy to move on to another brewery. Brewing with quality requires a high level of awareness of the procedures, the materials, and the equipment used in brewing. Our goal in this book is to address essential concepts in quality and consistency to help the readers become better brewers. At the conclusion of most chapters are review questions to check for understanding, followed by a case study for critical analysis and discussion.

We make extensive use of primary and secondary references, but we deliberately omitted all in-line references and any citations that might be distracting to the student. Useful and critical references are mentioned at the end of each chapter under "Bibliography." Many of the facts that we present were won by the brilliant insights and very hard work of thousands of scientists. We herewith acknowledge their contributions, even if, for the benefit of readers, we did not give them citations. We hope that this approach will be more effective than voluminous citations in putting the work of our colleagues into the hands of students, who will be the next generation of brewers and brewing scientists.

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Donna-Marie Zoccoli and Dr. David Barth, our eagle-eyed copy readers, read the manuscript multiple times, corrected errors, and made countless suggestions that make the book easier to read and understand. Dr. Naomi Hampson took some outstanding photographs. Kent Pham, Dave Goldman, Michelle McHugh, and Eric Jorgenson provided additional pictures. Our friends at Deer Creek Malt House, Philadelphia Brewing Company, Sly Fox Brewing Company, Susquehanna Brewing Company, Victory Brewing Company, Yards Brewing Company, and Yuengling Beer Company were generous with their time and gave us insights, explanations, and access for photographs. Our professional societies, The American Society of Brewing Chemists (ASBC) and the Master Brewers Association of the Americas (MBAA) maintain outstanding resources and networking opportunities that were critical to our own development as brewing chemists. Our institutions (University of the Sciences in Philadelphia and West Chester University) and their libraries and librarians provided essential support. Our editors at Wiley, Jonathan Rose, Aruna Pragasam, and Viniprammia Premkumar, have been supportive, helpful, and responsive. Our students motivated the entire project with their enthusiasm and unquenchable desire to learn.

We are forever grateful to the supporting words and actions of our own teachers and mentors in years past. Dr. Farber acknowledges Dr. Peter Berget for his mentorship and Dr. Angela Weisl for the inspiration to pursue writing. Dr. Farber is incredibly thankful for his parents, Dr. Phillip and Larice Farber, for instilling endless curiosity and creativity in him. Dr. Barth acknowledges his physical chemistry teacher and father, the late Dr. Max Barth; his high school chemistry teacher, Mr. Dugan; and his high school English teacher, Mr. Martini, who taught the importance of clarity and precision in writing.

CHAPTER 1

BREWING QUALITY OVERVIEW

We wrote this book to help you to better understand, appreciate, and apply the science behind the materials and processes of making **beer**. The better your grasp of **brewing** science, the more dependably you will be able to make delicious beer, and the more reliably you will be able to devise new beers to meet changing consumer preferences. So what is beer? How does beer differ from its **fermented beverage** brethren? There are legal and marketing definitions, but in a book on brewing science, we will use a scientific definition. Beer is an undistilled **alcoholic beverage** derived from a source of **starch**. "Derived from" covers a complex series of interacting steps, each of which influences the character of the final product and is ultimately the focus of this book. Brewing beer differs from **fermentation** of **wine** in that for brewing, a source of starch must first be converted into **fermentable sugars**. The brewer is responsible for management and control of all steps of the brewing process to produce a beer of reliable and reproducible quality.

There are four main ingredients in beer: water, **malt**, **hops**, and **yeast**. If randomly combined, these four ingredients might turn into an alcoholic beverage of questionable quality, but in this chemical process, the brewer is like an **enzyme**, a substance that guides and speeds up a **reaction**. Mastering

Mastering Brewing Science: Quality and Production, First Edition.
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the science of raw materials and the process steps of beer production is essential to making quality beer. Here, we will start with a broad overview of the brewing process followed by a scientific history of beer and the scientific method. In learning how to conduct an experiment, you will begin to understand the process of troubleshooting problems in the **brewery**. And finally, as our major goal is to brew beer of excellent quality and consistency, we will discuss beer quality as defined in several contexts. Each of these topics will be discussed further in depth in the chapters that follow.

1.1 INGREDIENTS

In addition to the main ingredients, beer is often brewed with other ingredients. These can include **adjuncts**, which are sources of starch or **sugar** other than malt, and processing aids, which are materials used to help give the beer desirable characteristics. Some common processing aids are **finings**, which help to clarify the beer; carbon dioxide, which **carbonates** the beer; **foam** enhancers, which provide desirable foam properties; and colored materials, which are used to adjust the color of the beer. In this introduction we will touch upon the main four ingredients. Adjuncts and processing aids are covered in later chapters.

Water

Beer is usually more than 90% water. It can take as much as 12 volumes of water to make 1 volume of beer. Some breweries have been able to cut this ratio to three or less. Less water means less **energy** use, less waste material to dispose of, and less negative impact on the environment. Water itself is a characterless **compound** of fixed composition. Water supplied to breweries is a **mixture** with many desirable and undesirable **components** present in trace amounts. The nature and amount of these trace components is important to the character and quality of the beer. Water is usually processed to adjust the trace components. Water that is to be made into beer is sometimes called **brewing liquor**. Chapter 4 discusses brewing water in detail.

Malt

Brewing beer requires starch, the source of which is **cereal grain**. At least some of the grain is ordinarily processed to give malt, a process called malting. Malt is seeds of grain that are germinated and then dried. The most common grain for malting is **barley**, but wheat, rye, and oat malt are available. Rice and

maize (**corn**) can be malted, but these malts are strictly specialty items; they are rarely used in beer brewing. Since medieval times, malting has been a separate craft from brewing, and malt is produced in specialized facilities. Brewers need a basic understanding of the malting process to make the most effective use of the available varieties of malt.

Malting begins by **cleaning** live seeds of grain over a series of sieves. The grain is then **steeped** (soaked in water) at a controlled **temperature**, typically in two to three stages of steeping and draining. The grain is then permitted to **germinate**. It must be kept in contact with air to support **respiration** and to carry away **heat** generated by the life processes. The seeds are regularly turned to expose them to oxygen and to maintain a uniform temperature, avoiding hot or cold spots. Regular turning also prevents sprouting roots from becoming tangled. The germination process produces several changes in the seeds, collectively called **modification**. **Enzymes** are produced that assist the modification process. Some of these enzymes are also critical to the brewing process in that they are responsible for converting the starch to sugar during **mashing**. Certain **polymers**, including **proteins** and **beta-glucan**, are **hydrolyzed** into smaller **molecules** under the influence of the enzymes. After modification, the seed loses its pebble-like hardness and becomes **friable** (easily crushed). Some of the starch in the seeds is consumed as fuel to power the life processes of the **embryo**. This is called malting loss. When the **maltster** judges that germination has proceeded far enough, the seeds are transferred to an oven, called a **kiln**, and heated with moving air. Different grades of malt are produced by varying the degree of modification and the temperature and duration of heat treatments. Shorter kiln times at lower temperatures yield malt with more starch-hydrolyzing enzymes and less **flavor**. Longer, higher temperature kiln treatment yields darker, more highly flavored malts, but with a lower enzyme content. Some malt is subjected to additional heating, called roasting, to give dark, highly flavored but nonenzymatic malt. Chapter 4 covers the malting process in detail.

Hops

The **hop** is a climbing plant, ***Humulus lupulus***. The fruits of the hop plant, hops, are boiled with the beer **wort** to provide bitterness and other flavors. Hop compounds also have an antibacterial effect that can help preserve the beer. Sometimes hops are added at other points in the brewing process to provide desired flavor effects. There are many varieties of hops with different flavor profiles. In addition, there are products derived from hops that are often used instead of or in addition to the natural hops. Chapter 4 provides details about hops and their processing.

Yeast

Yeast is the single-**cell fungus** that converts sugar to **ethanol** and carbon dioxide. The action of yeast on sugar is fermentation. Most beer fermentation is carried out by one of two species of yeast, ***Saccharomyces pastorianus***, used for **lager beer**, and ***Saccharomyces cerevisiae***, used for **ale**. Some specialty beer styles are fermented with ***Brettanomyces*** *bruxellensis*, *Brettanomyces lambicus*, or related species. Within a particular yeast species, there are many variations, called **strains**. The species and strain of yeast affects the character of the beer. Yeast is often cultivated at the brewery. Processes and practices involving yeast are covered in detail in Chapter 9.

1.2 BREWING OVERVIEW

A graphical overview of the brewing process is provided in Figure 1.1. In brief:

- Malt and other grains are crushed in the **mill**. Crushed grain is called **grist**.
- The grist is loaded into the grist case until mashing.
- The grist is mixed with hot water in the **premasher** on its way into the **mash tun**.
- In the mash tun, enzymes from the malt cause the starch in the grist to be converted to soluble **extract**, which contains sugars that the yeast can ferment.
- The **solution** of extract, called wort, is separated from the remaining grist particles in the **lauter tun**. Extract that sticks to the particles is washed out with hot water in a process called **sparging**.
- The clear wort is boiled in the **kettle**. Hops are added.
- The remains of the hops and solids that form during boiling (**hot break** or **trub**) are removed in the **whirlpool**.
- The clear, boiling hot wort is cooled in a **heat exchanger** called the **chiller**.
- The cool wort is **pumped** into a fermenter. Yeast is added (**pitched**).
- After several days of fermentation and **conditioning**, the yeast is removed from the beer, and the beer is pumped into the **bright beer tank**. Carbon dioxide is added under **pressure**.
- The beer is served or packaged.

A summary of the duration and temperature ranges for each step in the brewing process is provided in Table 1.1. This table represents a general summary and overview; different breweries using different equipment and brewing different styles of beer may have quite different programs.

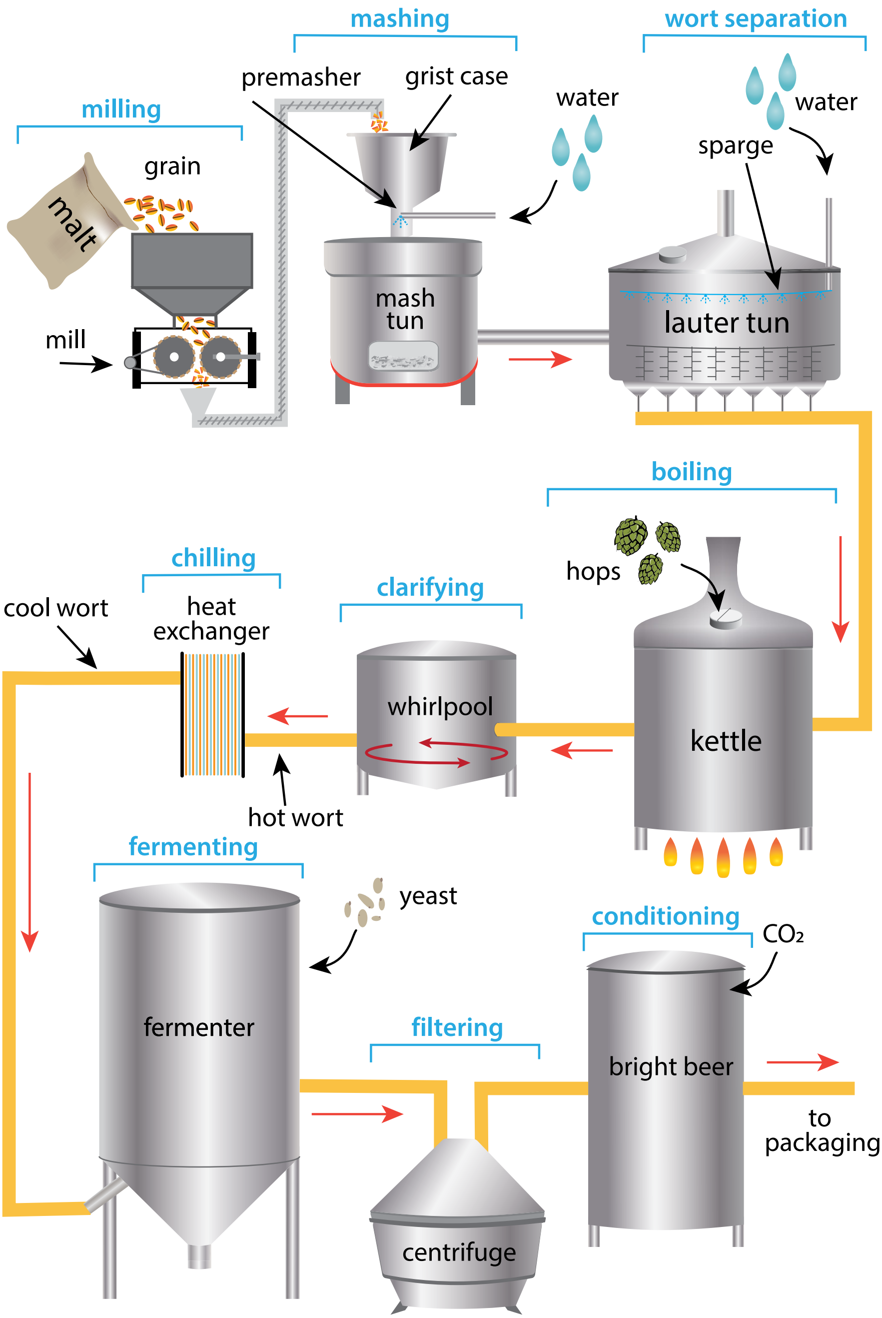

Figure 1.1 Overview of the brewing process for a four-vessel brew house.

TABLE 1.1 Brewing Steps, Durations, and Temperatures

Process Step	Duration	Temperature
Milling	1–2 hours	Ambient
Mashing	1–2 hours	45–67 °C
Lautering/sparging	1–2 hours	75–78 °C
Boiling	1–2 hours	105 °C
Whirlpool	15–30 minutes	76–74 °C
Fermentation (ale)	4–10 days	15–25 °C
Conditioning (ale)	2–14 days	−1 to 6 °C
Filtration	2–12 hours	2–6 °C
Packaging	<12 hours	2–6 °C
Duration of typical shelf life	~6 months	2–6 °C

Figure 1.2 Brew house at Victory Brewing Company.

Brew House

The **brew house** (Figure 1.2) is the facility that makes beer wort out of water, malt, adjuncts, and hops. Brew house operations involve hot water or hot wort, so the brew house is sometimes called the *hot side*. Because one of the last steps in this process is boiling the wort, the brew house presents less of a concern for **microbial spoilage** than the **cellar**. The brew house operations are milling, mashing, **wort separation**, boiling, and chilling.

Milling Malt is delivered to breweries in bulk or in bags. Before use in brewing, malt must be crushed into small pieces to extract the starch. The physical operation involved is milling. Crushed grain is called grist. The device

Figure 1.3 Mill at Susquehanna Brewing Company.

that performs the operation is a mill (Figure 1.3). The primary purpose of milling is to allow starch from the grain, enzymes from malt, and water to come into contact during the mashing step. A seed of grain is protected by a water-resistant **seed coat**, also called the **testa**. Milling breaks open the seed coat and crushes the interior of the seed, producing additional **surfaces** at which water can react with starch. Milling details have a significant effect on the character of the beer and the efficiency of the process. It is essential that the malt **hulls** be split but not pulverized. They will aid in a later step, wort separation.

Mashing During the mashing step, starch is converted to smaller sugars that brewing yeast can ferment. Yeast cannot ferment starch, so this step is essential. During mashing, hot water, sometimes called brewing liquor, is mixed with the grist to give a temperature in the range of 60–70 °C (140–158 °F). Sometimes mashing starts at a lower temperature, and the temperature is raised continuously or in steps to influence the protein or **carbohydrate** profile. Mashing is conducted in a **mash conversion vessel** (**MCV**), also called a mash tun (Figure 1.4). The mash tun may contain an agitation paddle for gentle mixing. The details of the time–temperature profile, the activities of

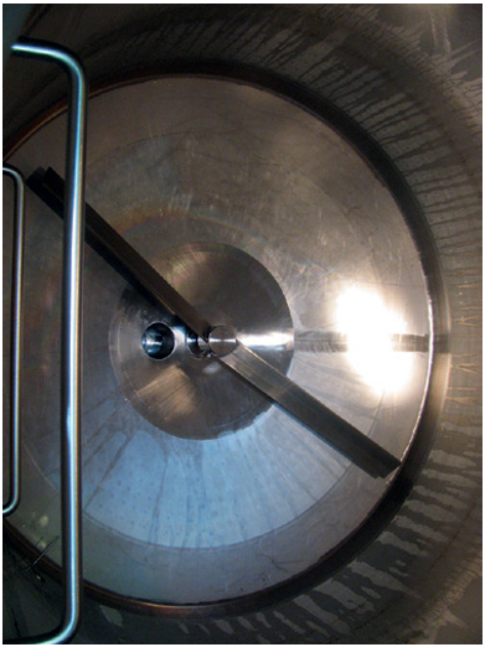

Figure 1.4 Inside the mash tun at Victory Brewing Company.

enzymes derived from malt, and the **pH** of mashing have a decisive effect on the character of the beer.

Three processes must occur for effective mashing. The first is **gelatinization**, in which starch granules absorb water, swell, and burst, giving the starch molecules access to water. Some grains, including barley and wheat, gelatinize readily in the normal mashing temperature range. Others, like maize (corn) and rice, must be cooked in a separate vessel before addition to the mash. The second process is **liquefaction**, in which starch molecules are hydrolyzed in the interior of the molecular chain to give soluble, but still too large for fermentation, fragments. The third process is **saccharification**, in which starch chains and fragments are further broken down at the ends of the chains to yield the fermentable sugars: **glucose**, a **monosaccharide**; **maltose**, a **disaccharide**; and **maltotriose**, a **trisaccharide**. Mashing temperature plays a key role in determining the fraction of starch that is liquefied and the fraction of dissolved carbohydrate that is fermentable.

The amounts of unfermentable and fermentable carbohydrates are determined during mashing, influencing the character of the finished beer. The generation of more fermentable sugars results in a thinner, dryer beer with more alcohol. A mash with less fermentable sugars leads to less alcohol but more body and texture.

Wort Separation After mashing, the wort, the insoluble material, and the broken hulls remain in a **slurry**. Wort separation is required to obtain clear wort. The solids remaining after separation are called **draff** or spent grain. Two methods of wort separation are in common use. The most popular is the lauter process [Ger: clear, pure]. In this process the solids are supported on a perforated **false bottom** above the true bottom of the vessel. Liquid is drawn through the grain and the false bottom via **valves** in the true bottom. The actual **filtration** is accomplished by the grain bed, the split hulls from the malt. The false bottom supports the grain bed and facilitates separation. In the first minutes of wort separation, wort is recirculated to the top of the vessel. Recirculation, called **vorlauf** [Ger: forerun], is maintained until the wort runs clear, indicating the grain bed is set. If the mash and lauter are accomplished in the same vessel, this is called a mash/lauter tun. Often the entire mash, liquids and solids, are pumped into a separate, dedicated vessel called the lauter tun (Figure 1.5). The lauter tun is equipped with knives or rakes that slowly dig into the grain bed to increase the filtration speed. A different lautering device, less common in small breweries, is the **mash filter**. Here the entire mash, including liquids and solids, is pumped into compartments from which the liquid is driven by pressure through filtration material.

During or after lautering, the grain is rinsed with hot water, a process called **sparging**. Sparging recovers sugar that is held up in the grain bed, so more beer can be made from less grain.

Figure 1.5 A peek into the lauter tun at Urban Village Brewing Company. *Source*: Photo: Dave Goldman.

Boiling The clarified wort is sent to a vessel called a brew **kettle**, also called a **copper**, or a wort boiler (Figure 1.6) and heated to boiling. The wort is usually boiled for 60–90 minutes with evaporation of up to 20% of the wort volume. Boiling consumes the most energy of any step of the brewing process. Hops or hop products are generally added before or during boiling, often in stages so that different portions of the hops are subjected to different boiling durations. Boiling serves several purposes, including the following:

- **Isomerization** of hop compounds for bitterness.
- **Sterilization**.
- Dissipation of **off-flavors**.
- Removal of proteins and **lipids** that affect beer clarity and stability.
- Concentration of wort.

Boiling generates solid material called hot break or trub ("troob"). Sometimes the hot break material is removed before chilling, either by allowing it to settle (**sedimentation**) or in a vessel called a whirlpool, in which

Figure 1.6 Brew kettle at Yuengling Beer Company.

the wort is made to move in a horizontal circular pattern that drives the solids into a compact mound at the bottom center of the vessel. In some breweries the kettle itself also serves as the whirlpool.

Chilling Before fermentation, the temperature of the wort must be lowered from near boiling (100 °C or 212 °F) to the fermentation temperature (typically 9–20 °C or 48–68 °F), a process called chilling. The standard equipment for chilling is a **countercurrent** plate heat exchanger. The **unit** consists of a series of closely spaced and parallel heat-conducting plates, as shown in Figure 1.7. The hot wort flows through half of the channels between the plates, and a coolant, typically water or an **antifreeze** mixture, flows through the rest. Each plate has wort on one side and coolant on the other. Typically, the outgoing water, which is now hot, is added to the **hot liquor tank**, to be used for later brewing operations.

In some traditional breweries, the hot wort is drawn into a wide, shallow vessel called a **coolship**, where it is slowly cooled by convection. A few breweries use this method to capture wild **bacteria** and yeast, but most brewers prefer a closed chiller to avoid the risk of contamination.

At the beginning of fermentation, the yeast needs dissolved oxygen (as a nutrient, not for respiration) to help prepare cell **membranes**. Because the

Figure 1.7 Chiller at Philadelphia Brewing Company.

boiling process strips the wort of all dissolved **gases** and because gases are more soluble at cooler temperatures, oxygen is injected into the wort as it exits the chiller. The oxygen requirement depends on the solids content of the wort and on the strain of yeast.

Cellar

Before the days of mechanical refrigeration, fermentation and conditioning were often carried out in an underground room, or even a cave, called the cellar. Figure 1.8 depicts the underground caves at the Yuengling brewery in Pottsville, PA, where beer was formerly **lagered** and conditioned. Today, fermentation and conditioning temperatures are usually controlled artificially in the tanks themselves, and the "cellar" can be at any level of the brewery. The cellar is sometimes called the *cold side*.

Fermentation Cooled, aerated wort from the chiller is transferred to a fermenter, also called a fermentation vessel (**FV**). The most widely used configuration for the fermenter is the **cylindroconical** vessel (CCV), shown in Figure 1.9. A selected strain of yeast is added or pitched into the wort. Fermentation converts certain sugars to ethanol and carbon dioxide. The reaction is carried out by yeast, a single-celled fungus, as a means for the yeast to make cellular energy in the absence of oxygen. Fermentation occurs in 12 distinct steps. The overall reaction is $C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$. In addition

Figure 1.8 Caves at Yuengling Beer Company.