BEER

TAP INTO THE ART AND SCIENCE OF BREWING

SECOND EDITION

CHARLES BAMFORTH

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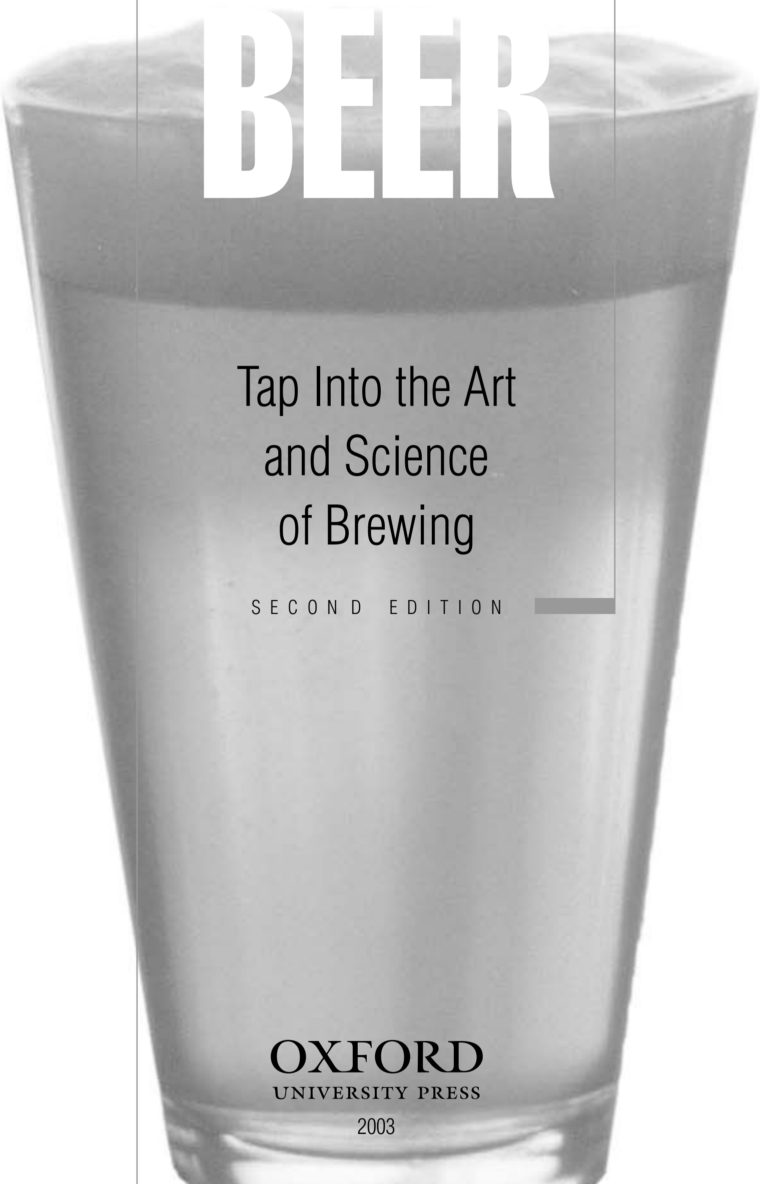

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For Diane, Peter, Caroline, and Emily

They who drink beer will think beer.
—Washington Irving

You can't be a Real Country unless you have a beer and
an airline–it helps if you have some kind of a football team,
or some nuclear weapons, but at the very least you need a beer.
—Frank Zappa

In my opinion, most of the great men of the past were
only there for the beer.
—A. J. P. Taylor

God has a brown voice,
as soft and full as beer.
—Anne Sexton

Foreword

Doug Muhleman

I would like you to imagine for a moment that beer did not exist on our planet in any shape or form. Is it possible, or even probable, that anyone would invent this beverage as we know it today? And even if someone did "invent" beer, would they be able to convince any rational-minded businessperson to invest in the concept?

The answer, of course, is no. The process of brewing beer is a complex, somewhat convoluted, and, at times, mysterious endeavor that has evolved from what was probably a prehistoric accident.

The truth is, the average beer drinker today probably has very little understanding or appreciation of what goes into producing his favorite six-pack. And no wonder! This simple beverage, that is consumed by millions of people around the world every day and is taken for granted by most who enjoy it, is produced by a process that many would regard as modern-day alchemy.

Professor Bamforth (Charlie) wrote the first edition of *Beer* to unveil and explain this process in a meaningful, accurate and digestible form. In this newest edition, revised and updated, Charlie has added a new dimension to his original excellent text by further giving the reader a glimpse of the interplay between the process and the people who make it happen.

Charlie's creativity, sense of humor and wit, and unique perspective on beer and brewing come through at an even higher level in this new edition. Charlie is a world-recognized authority on beer and brewing, and there is no doubt that this man loves beer.

Achieving the taste characteristics of a fine beer is truly a combination of art and science. The quality of the beer is dependent not only on the quality of the ingredients and the process but also on the quality of the knowledge, understanding, and experience that went into making it. In this book, Charlie vary capably provides this very important foundation.

Whether you are a brewmaster, a marketer, an amateur brewer, or a beer enthusiast, this book will enrich and expand your understanding and appreciation of this noble beverage.

Preface

Not long before leaving England to take up my role as professor of malting and brewing sciences at the University of California, Davis, in February 1999, I was the guest on a local radio show in Guildford. Two questions I remember well.

The first was: "Charlie, did you think as a young boy at school in Lancashire that you would one day be the beer professor in California?" to which the instinctive reply, of course, was: "Well, it'll be a lousy job but I guess somebody has to do it. Must be my debt to society." I was, of course, using irony, lest anybody think I meant it!

The second question was more irritating. "Charlie, how will you possibly be able to enjoy those weak and tasteless beers over there after so long drinking our lovely English ales?" I was composed, replying thus:

> It's horses for courses. If I am in a 300-year-old thatched West Sussex pub, my bald head scraping the ceiling, snow outside, a roaring log fire within, a plate of shepherd's pie to devour from atop a well-scrubbed oaken table of great antiquity, then a pint of flat, generously hopped ale is a delight. However, if I'm in a baseball stadium, seventh inning stretching with a pile of nachos topped with jalapenos and 40 degrees of Mr. Celsius's best frying my few follicles, then an ice cold Bud is to die for. And, by the way, if you're talking "weak," then do remember that a U.S. lager will typically contain 20% more alcohol (at least) than an ale from England.

On that occasion they didn't ask me the usual question beamed at a brewing professor: "But what is your favorite beer?" Usually I reply, "One that's wet and alcoholic," which is, of course, something I don't believe. Just like there are good and bad footballers, and good and bad vicars, indeed good and bad virtually anything, then there are certainly beers (rather too many of them) that are plainly deplorable. Unquestionably, though, the great Brewers of the world invariably delight the customer with their wares. A great many gently flavored lagers are superb, and so wonderfully consistent. They have to be, for they are unforgiving and will reveal any conceivable shortcoming in raw material, process, or packaging. Equally, I can take you to some intensely flavored ales that are completely out of balance and devoid of all drinkability. There is no simple correlation between excellence and depth and complexity of flavor.

Which is why I get hopelessly infuriated with self-styled beer gurus who pontificate about what an ale or a lager should or should not be and about what should and what should not be the raw materials and processes that ought to be used, without the remotest understanding of the real science and technology of the brewer's art and the trials and tribulations of everyday existence in a brewing company.

This book attempts to give a reasoned view on such issues from the perspective of a longtime brewing scientist, research manager, quality assurance manager, customer, and, latterly, the bloke with the best job in the world.

Preface to the First Edition

A year or two ago I was idly flicking between television channels when I chanced upon a couple of people sipping beer and discussing their findings. One of these people has established a reputation as being something of a wine connoisseur and would appear to take particular pride in pinpointing the exact vintage of the bottle and the winery in which it was produced. For all I know, that person may be able to name and give the shoe size of the peasant who trod the grapes. With rather more certainty, however, *I* was able to conclude that this person's knowledge of beer was mediocre, or worse.

From time to time, too, I come across articles in the general press, that pontificate about beer in a manner not unlike that of this wine buff. I applaud the efforts of some of these authors to help maintain beer in the collective consciousness. I deplore it, however, when they attempt to preach on the rights and wrongs of brewing practice. It is galling when they dress up the taste and aroma of beer in ridiculous terminology. Personally, I have enormous difficulty reconciling the language they use with the tastes of the myriad of beers that I have had the great good fortune to consume across the world.

An analogous situation exists in my own "other life." While it is research into the science of brewing and beer that pays my mortgage and puts food in the mouths of my children, my hobby is to write articles about soccer. I hope (and believe) that they help contribute to the pleasure of the fans who read them, but I hope I would never be accused of trying to tell the professionals within the game of how to do their jobs. I might fairly articulate the views of an "outsider"—the fan's-eye view—but I trust that it's the coaches and the players within soccer who know their specialization and can deliver a product that will thrill and delight me.

Rather more is written about beer in the nonspecialist press by "fans" than by "professionals." There is room for both—and that is why I decided to write this book, in an attempt to partly redress the balance. In it, I have attempted to capture the proud history of brewing, which stretches back to a time when articles on the merits of beer will have been written on papyrus or scrawled in hieroglyphics on walls of clay. I have attempted to convey the somewhat complex science of brewing in straightforward terms, with particular emphasis on why the properties of beer are as they are. I have endeavored to show what are the sensible and meaningful ways in which beer quality can be described. And I have tried to entertain, without trivializing a proud and distinguished profession.

I like beer, and, like the majority of people working in the brewing industry, I care about it and about the people who drink it. In this book I draw attention to a myriad of recent studies that suggest that beer (and other alcoholic drinks) are beneficial components of the adult diet, provided they are consumed in moderation. I certainly have no intention of encouraging the irresponsible to abuse the pleasure that comes from drinking beer in moderation, at the right time, in the right place.

I want people to understand and appreciate their beer and to gain an insight into the devoted labors of all those whose combined efforts bring it to the glass: the farmer who grows the best barley; the hop grower cultivating a unique crop; the Maltster, who converts barley into delicious malt; the Brewer who combines malt and hop to feed a yeast that they and their predecessors will have protected for perhaps hundreds of years; the bartender who keeps the beer in top condition.

This book is about facts. Where there is scope for expressing opinions, then these are my own, and not everyone in the brewing trade will necessarily agree with them. They have, though, been arrived at in a career in the brewing profession approaching 25 years. From reading this book I hope you will form a considered opinion about brewing and about beer—and become rather better acquainted with its art and science.

Acknowledgments

Through my scientific career I have been fortunate in having a number of guiding lights, without whose interest it would have been impossible to contemplate this small book. It was my Ph.D supervisor, Peter Large, who taught me the pleasures of research—and of good ales in the pub paradise that is Hull. My post-doc with Rod Quayle, F.R.S., in Sheffield, was perhaps the most delightful and productive stage of my career in England. In 1978 I was brought into the industry by John Hudson, a redoubtable Yorkshireman who placed enormous stock in the proper use of the English language. Director of the Brewing Research Foundation at the time was Charles Dalgliesh, the first person in the industry to champion my work and to encourage one to have the courage to stand up to dyed-in-the-wool dogma. I was taken into the Bass fold by Tony Portno, a fellow Lancastrian and equally blunt spoken, and then nurtured into the ways of the famed Red Triangle by Stuart Molzahn. It was Tony who insisted I have my smooth academic edges roughened by a stint at the "coal face," and him I must thank for the invaluable experience of being quality assurance manager at Bass's most modern brewery. Another Lancastrian and true visionary, Bernard Atkinson, took me back to the Brewing Research Foundation and pointed me to an international awareness. At this time, also, I was honored to be made visiting professor of brewing at the International Center of Brewing and Distilling at Heriot-Watt University, Edinburgh, Scotland, allowing me to work closely with my very big buddy Graham Stewart.

Thence, early in 1999, to California, thanks to the generosity of Anheuser-

Busch in endowing the Chair of Malting and Brewing Sciences at the University of California, Davis. In particular I thank Doug Muhleman (Group Vice President, Brewing Operations and Technology, Anheuser-Busch, Inc.), champion of this endowment and inspiration. I thank him, too, for sparing some of his formidable schedule to pen the foreword to this volume. At Davis I grabbed the baton and great encouragement from Michael Lewis, a gifted teacher and valued friend.

Countless coworkers, students, and friends have shared my adventure in beer and brewing—and hopefully there will be plenty more to come. Some things, though, always remain constant, above all the love and support of my wife, Diane, and our children, Peter, Caroline, and Emily. Once more I dedicate my book to them.

I thank my publishers, notably Kirk Jensen, for their patience and interest. Special thanks to Dr. Bill Vollmar, corporate historian of Anheuser-Busch, Inc., for access to his vast resources, and to Steve Harrison and Noah Ceteras of Sierra Nevada for much valuable material. Acknowledgment of the suppliers of other illustrative material is made in the legends to the figures.

Contents

Introduction

Ralph Waldo Emerson (1803–1882), the great American essayist, poet, and one-time Unitarian minister, penned many learned thoughts. The reader will forgive me if I select just 13 words from the great man: "God made yeast . . . and loves fermentation just as dearly as he loves vegetation."

Beer, surely, is a gift of God, one that brings together yeast and vegetation (in the shape of barley and hops) in a drink that has been enjoyed for 8,000 years, a beverage that has soothed fevered brows, nourished the hungry, and coupled friendly and unfriendly alike—it's even seen men off into battle. "No soldier can fight unless he is properly fed on beef and beer," said John Churchill, the first duke of Marlborough (1650–1722), a great British tactician and a forebear of the even more celebrated Winston.

Queen Victoria (1819–1901) was another who recognized the merit of beer: "Give my people plenty of beer, good beer and cheap beer, and you will have no revolution among them." With these sentiments, the redoubtable monarch echoed the enthusiasm of the Athenian tragedian Euripides (484–406 BC):

> The man that isn't jolly after drinking
> Is just a driveling idiot, to my thinking.

This book is not an exercise in trying to convince you, the reader, of the merits and demerits of drinking beer. I assume that as you have picked it up, and are starting to read, you have an existing interest in beer. The aim of this book is to give the nonspecialist a feel for the science and technology that underpin a truly international beverage. I use the word "international," accepting that to do justice to the entire world of beer would have demanded more than a single volume. Markets differ considerably from country to country, but the scientific principles of brewing are constant the world over. It is the science and the technology about which I particularly wish to inform the reader, for the processes involved in the brewing of beer are as fascinating as they are, in some ways, unique.

I have several audiences in mind for this book. First, and perhaps foremost, are the laypeople who want to know, in reader-friendly terms, what goes into their beer. Such people seek to understand the magic that underpins this supreme alchemy, namely the conversion of barley and hops, by yeast, into something so astonishingly drinkable. My desire is to reinforce the pleasure people take in responsibly drinking beer by informing them about the myriad of biochemical and chemical reactions that are involved in the production of their favorite drink and by exposing them to the enormous reservoir of science and technology that makes malting and brewing two of the great "traditional" industries. It is my earnest hope that, by reading this book, beer drinkers will come to appreciate the care that goes into making every pint of beer. I will be describing a science, or rather, a range of sciences, and so can't avoid using scientific terms. Hopefully I have achieved this in a way that is readily understandable for those without mastery of chemistry, biology, physics, chemical engineering, and the other scientific disciplines on which brewing is founded. I have provided a simple explanation of the underpinning science as well as a comprehensive glossary at the end of the book.

A second group of people who should benefit from reading this book are those who are joining the brewing industry and who wish to have a "friendly" introduction to humanity's oldest biotechnology. Among these readers will be those entering in nontechnical roles: sales, marketing, finance . . . chief executives!

Third, there are those who interact professionally with brewing, either as suppliers or retailers, and who need to know why the Brewer is so demanding in its requirements and is so very proud of its heritage (I use *Brewer* [or *Maltster*] with a capital letter when referring to a brewing [or malting] *company,* but *brewer* and *maltster* in the lower case when describing an individual practitioner of the art).

A valued colleague has extremely strong views on the use of language in books and lectures about the brewing business. I well recall having finished giving a lecture in Canada that I thought had gone across very nicely, when she stormed up to me, asking darkly whether I had a view on whether women as well as men drank beer. Puzzled, I replied, “Of course they do.” “Then why,” she replied, acidly, “did every reference to the beer drinker in your talk consist of ‘he this,’ ‘he that.’” I had meant no offense by it, using “he” in the generic sense, but I haven’t made the mistake since. For this reason, I intersperse the words “he” and “she” throughout this book. As we will see in chapter 1, it was the female of the species who was once primarily responsible for brewing the ale; she was called the “brewster.”

Another problem I had to confront was the matter of units. Brewers in different countries have their own scales of measurement. Even when the same name is used for a unit, it doesn’t necessarily mean the same thing in different countries. Thus, a barrel in the United States comprises 31 gallons, whereas a barrel in the United Kingdom holds 36 gallons—and just to complicate matters further, a U.S. gallon is smaller than a U.K. gallon. I have used both types of “barrel” at various points and have indicated whether it’s a U.S. or a U.K. variant. The international unit for volume, however, is the liter or the hectoliter (hl; 100 liters). By and large, this and other metric terms are employed because Brewers across the world do tend to use them, as well as their own parochial preferences. A gallon equates to 3.7853 liters in the United States; hence a U.S. barrel holds 1.1734 hectoliters (hl). A U.K. barrel, on the other hand, contains 1.6365 hl, because 1 U.K. gallon equals 1.201 U.S. gallons.

When I talk about the alcoholic strength of beer, it is always as % vol./vol., which many people refer to as “alcohol by volume” (ABV). Thus a strength of 5% ABV indicates that there are 5 ml (cm^3) of alcohol (ethanol, previously known as ethyl alcohol) per 100 ml of beer. Although Brewers in the United States still frequently use the Fahrenheit scale (and even, until relatively recently, the Reaumur scale, in which pure water freezes at 0° just as on the Celsius scale, but its boiling point is at 80°), I have used degrees Celsius throughout, as it is generally understood in all parts of the world and is increasingly employed in American brewing literature. (Those of you who find Celsius a mystery will need to apply the correction factor $°F = °C \times 9/5 + 32$.) Finally in connection with units, from time to time I talk about the levels of other molecules in beer, especially the substances that contribute to flavor. By and large these are present at quite low concentrations. You will find mention of ppm, ppb, and ppt: these refer to parts per million, parts per billion, and parts per trillion, respectively. A substance present at 1 ppm exists as 1mg (milligram) per liter of beer. One ppb equates to 1 μg (microgram) per liter of beer, while 1 ppt means 1 ng (nanogram) per liter of beer. One mg is a thousandth of a gram; 1 μg is a thousandth of a milligram; 1 ng is a thousandth of a microgram. (Just in case the metric system still leaves you cold, I had better point out that there are 28.35 grams per ounce and 128 fluid ounces per U.S. gallon.)

I also had the thorny question of which currency to use. As this book emanates from a New York publisher, I have chosen to use dollars and cents. Finally, when presenting statistical data, I have used the most recent information available to me. I regret that much of the trend information takes rather a long time for researchers to collect, so some details are a year or two old now.

Enjoy the book—and savor the beer that is the end result of so much care and devotion.

1

From Babylon to Busch

The World of Beer and Breweries

The World Beer Market

Beer is drunk all over the world. In some places, such as parts of Germany, it is *the* drink of choice for accompanying food. I well remember sitting in a restaurant near Munich witnessing the arrival of a coach loaded with elderly ladies and being astonished to see them demolish liters of lager, whereas the grannies I had been used to in England sipped tea. Across the globe, beer is the great drink of relaxation—and moderation. It is consumed in bars, clubs, sports grounds—in fact anywhere adults congregate. Surely nowhere typifies this better than the English public house (or "pub"), which remains, alongside the church, the essential ingredient of any self-respecting community, albeit changed, insofar as food rather than beer seems now to be the prime magnet in many hostelries.

Yet it is clearly not essential to have company to pursue one's favorite tipple. In the United Kingdom, for instance, the proportion of beer sold on draft has declined from 78.3% when I first joined the industry in 1978 to 62.4% in 1999. Furthermore, in that time the proportion of beer sold in nonreturnable bottles (NRBs) has leaped from 0.5% to 10.5% of all beer sold. In the United States of 1933, 68% of all beer sold was "on tap," but by 1990 that had declined to 11%. There has been a clear shift toward beer drinking domestically, driven in part by the increasing trend toward seeking one's social pleasures through entertaining at home or in more solitary pursuits such as watching television or thumping computer keys. As we shall see later, developments in technology have enabled traditional beers hitherto sold only in casks to be packaged in cans, leading to a major growth in what is called "draft beer in a can." The growth in volume of NRBs, increasingly the selection in bars globally, perhaps reflects nothing more than the emerging preferences of the younger drinker, for whom the right label on the right bottle in the right hand in the right location seems to be the primary driver for beer selection. Perhaps the subconscious is also at play: the original rationale for taking one's beer straight from a bottle you uncorked yourself was to avoid somebody slipping you poisons!

In the United States, 26% of the beer is purchased "on premises": that is in bars, restaurants, and hotels. Although this is a lower proportion than in, say, the United Kingdom, it is still the largest distribution vehicle for beer in the United States. Otherwise the beer is retailed via convenience stores and gas stations (20%), supermarkets (19%), liquor stores (17%), neighborhood accounts (7%), home distributors (5%), drug stores (4%), and warehouse clubs and supercenters (2%).

It would be impossible in a book of this size to fully explain the evolution of the brewing industry in each of the very many countries where beer is produced. Indeed, I could devote page after page to the many political forces that have come to bear on a commodity that will always attract all shades of public opinion. A classic example is the pressure that led to Prohibition in the United States between 1919 and 1933 (see "Prohibition"). This obliged the great Brewers to display a single-minded determination to thrive that remains a characteristic to this day and that ensures that one of the nation's Brewers is comfortably number one worldwide (table 1.1).

Certainly, the current status quo in world brewing is in favor of huge brewing concerns; 48% of the 1.33 billion hectoliters of beer brewed worldwide in 1998 came from just 10 companies. It is striking, too, that there are major breweries located in countries that do not have a high indigenous beer drinking population. In France, for example, personal beer consumption is 38.6 liters per head—less than a third of that drunk in Germany—yet the Kronenbourg breweries (acquired a couple of years ago from Danone by Scottish & Newcastle) have global sales over 200% higher than Germany's biggest producer. Brazil's beer consumption per capita is also far lower than that in Germany, yet it has one huge Brewer in the world top 10, AMBEV, formed by the recent merger of two already enormous entities, Brahma and Antarctica.

The brewing industry in Germany is somewhat traditional, as we shall see. It is characterized by many relatively small brewing companies, over 1,200 of them, mostly producing individual beers for local consumption. The biggest Brewer in Germany, the Binding group, produced some 11.2 million

Table 1.1
The World's Biggest Brewers

Company	*Country*	*Worldwide sales in 2000 (million hectoliters)*
Anheuser-Busch	United States	159.1 (23[a])
Interbrew	Belgium	76.9 (90)
Heineken	Netherlands	74.5 (91)
South African	South Africa	60.1 (61)
AMBEV	Brazil	57.3 (5)
Miller	United States	54.3 (9)
Carlsberg	Denmark	36.8 (91)
Asahi	Japan	31.4 (?)
Kirin	Japan	29.0 (32)
Scottish & Newcastle	United Kingdom	27.8 (49)

Source: Canning and Filling, January 2002.
[a]Values in parentheses are estimates of that company's sales outside its home country.

hectoliters in 1998, and that was 25% more than the next-biggest competitor. The biggest-selling brand in 2000 in Germany, Krombacher, sold no more than 4.6 million hectoliters. There are not many truly international German brewing brands, as indeed is the case for many other countries. It is largely the brands of some of the big 10 Brewers that stand alongside the great colas on the international stage, brands such as Budweiser, Heineken, and Carlsberg. Guinness is another gigantic world brand, produced by a company (Diageo) with an output of beer that only marginally excludes it from being among the "Big Ten."

As shown in table 1.2, beer production and consumption statistics differ enormously among countries. The United States brews 17% more beer than the next-largest producer, China. The United States, though, has a very sizable population. If the statistics are viewed on the basis of beer brewed per head, then Ireland easily leads the way.

The Czech Republic lays claim to the highest per capita consumption of beer, 33.4 liters more per year than that of their nearest challenger, Germany. In contrast, the Chinese drink only 15.6 liters per head, but because of the enormous population of that country they are the second-biggest producer of beer after the United States. Even more startling is the rate at which the Chinese beer industry has grown (see table 1.3). The volume of beer brewed in China has increased nearly a thousandfold in 30 years. Major brewing companies from other countries have formed joint ventures with local companies in China and have revolutionized the technology there.

Prohibition

The temperance movement began in the United States in the early nineteenth century, with 13 states becoming "dry" between 1846 and 1855, with Maine leading the way. Ironically, 1846 also marked the birth of Carry Nation (1846–1911, fig. 1.1), a *doyenne* among prohibitionists, whose prayers and lectures in Kansas developed into more physical acts of objection to drink when she and her followers started to smash beer containers with hatchets hidden beneath their skirts. The Anti-Saloon League was formed in Washington, D.C., in 1895, and gave the prohibitionists focus and organization. Widespread calls for prohibition were largely precipitated by claims that extensive drunkenness severely hampered productivity during World War I. Woodrow Wilson's Food Control Bill of 1917 was aimed at saving grain for the war effort, diverting it to solid food use and, to many, appeared to be an attempt to kill off beer. On January 26, 1920, the Eighteenth Amendment to the United States Constitution was enacted. This forbade the "manufacture, sale and transportation of intoxicating liquors" and was approved by all but two states. The Volstead Act of the same year was the basis on which the federal government enforced a block on all intoxicating liquor, defined as a drink containing in excess of 0.5% alcohol. Beer stocks were destroyed (fig. 1.2); 478 breweries were rendered unable to go about their primary business. One of the biggest names, Lemp in St. Louis, closed its doors forever. Others developed alternative products that their technology might be turned to, such as ice cream, nonalcoholic malt-based beverages (including "near beer"), yeast, and syrups.

Figure 1.1 Carry Nation. *Reproduced courtesy of the Kansas City Historical Society, Topeka, Kansas.*

Figure 1.2 *What a waste! Courtesy of the Beer History Society (beerhistory.com).*

Of course, for as many as were ardent in their anti-alcohol beliefs, there were those who enjoyed a drink. Unsurprisingly, the introduction of official Prohibition prompted the growth in illegal home brewing (of some dubious concoctions) and of the "bootlegging"/"speakeasy" culture colorfully portrayed in the movies. Before Prohibition there were 15,000 saloons in New York. One year after the Volstead Act, there were more than twice as many speakeasies! Gangsters grew rich at a time when the federal authorities convicted 300,000 people of contravening the law. Drink-related crime surged: for example, there was a nearly 500% increase in drunk-driving offenses in Chicago. People resented being prevented from partaking of something they enjoyed (fig. 1.3).

By 1933, opinion in the United States had changed (a slogan of Franklin Delano Roosevelt's Democrats was "A New Deal and a Pot of Beer for Everyone"), and on December 5, the Twenty-First Amendment to the Constitution, the repeal of the Eighteenth Amendment, was passed. Whether to enforce Prohibition or not became a state issue—and it took Mississippi until 1966 to emerge from being the last dry territory. For a company to return to brewing after such a hiatus (13 years for most states) is no trivial issue. In particular, there had been a loss of trained and skilled brewers and operators and much of the surviving equipment was unreliable, leading to equally "dodgy" products in many instances. It was the strong and the resourceful that survived, and inevitably this meant strength in size.

The United States is not the only country to have embraced prohibition—you can go back as far as Egypt 4,000 years ago to find the first attempts to control the sale of beer, it being felt even then that drinking interfered with productivity. Strong temperance movements grew up in Great Britain, largely in response to the perceived excesses of drink in the burgeoning industrial cities. People were urged to sign a "pledge" not to drink, but for many the soul was weaker than some of the ale! As recently as the 1950s in Canada one was obliged to purchase an annual permit to acquire alcoholic drinks. Prohibition was total in Finland for exactly the same period as in the United States.

A particularly vigorous temperance campaign was waged in New Zealand in the nineteenth and early twentieth centuries, which was perhaps ironic, insofar as the Englishman who "discovered" that land in 1769, Captain James Cook, also brewed the first alcoholic drink in New Zealand. A referendum after World War I, which passed 51 to 49 in favor of "continuance" of the liquor trade (thanks largely to the vote of the military), enabled the beer business to continue.

Perhaps the most curious of the "antidrink" movements was that in Germany in 1600. The Order of Temperance said that adherents should drink no more than seven glasses of liquor at one time and that there should be no more than two such sessions each day.

Figure 1.3 *Returning troops state their case. Courtesy of the Beer History Society (beerhistory.com).*

Table 1.2
Worldwide Brewing and Beer Statistics (1998)

Country	*Population (million)*	*Production (m hl)*	*Imports (m hl)*	*Exports (m hl)*	*Consumption (l per head)*	*Draft (%)*	*Average strength (% ABV)*
Argentina	36.1	12.4	0.39	0.18	34.9	1	4.8
Australia	18.5	17.5	0.21	0.43	95.0	24	4.3
Austria	8.1	8.8	0.36	0.51	108.1	32	5.1
Belgium[a]	10.6	14.6	0.88	4.9	99.0	40	5.2
Brazil	165.9	88.0	0.26	0.45	52.9	2	—[b]
Bulgaria	8.3	3.8	0.013	0.077	45.2	2	4.8
Canada	30.3	22.8	1.17	3.64	67.0	11	5.0
Chile	14.8	3.67	0.14	0.16	24.6	8	4.5
China	1,255.7	196.4	0.33	0.56	15.6	4	—
Colombia	38.3	18.3	0.5	0.04	48.9	1	4.2
Croatia	4.5	3.8	0.175	0.523	75.8	7	5.0
Cuba	11.1	1.25	0.046	—	11.7	—	5.0
Czech Republic	10.3	18.3	0.154	1.9	160.8	46	4.5
Denmark	5.3	8.1	0.079	2.4	107.7	10	4.6
Finland	5.2	4.7	0.08	0.32	79.1	23	4.6
France	58.7	19.8	5.3	2.4	38.6	26	5.0
Germany	82.0	111.7	2.8	8.4	127.4	20	—
Greece	10.4	4.0	0.19	0.3	42.0	5	4.9
Hungary	10.1	7.0	0.18	0.09	70.0	18	4.7
Ireland	3.6	8.5	0.56	3.45	124.2	80	4.1
Italy	57.5	12.2	3.68	0.37	26.9	16	5.1
Japan	126.4	72.2	0.8	0.71	57.2	16	5.0
Korea (Rep)	46.4	14.1	0.011	0.24	29.8	13	4.0
Mexico	95.8	54.8	0.37	7.79	49.4	1	4.0
New Zealand	3.8	3.21	0.181	0.14	84.7	40	4.0
Netherlands	15.7	24.0	0.95	11.7	84.3	31	5.0
Nigeria	106.4	4.2	0.008	0.006	3.9	0	4.5
Norway	4.4	2.2	0.045	0.011	49.7	27	4.5
Peru	24.8	7.2	0.014	0.031	29.0	1	—
Philippines	71.4	12.7	0.004	0.092	17.6	1	4.7
Poland	38.7	20.6	0.17	0.12	53.4	21	5.2
Portugal	9.9	6.8	0.29	0.55	65.3	28	5.2
Romania	22.5	9.9	0.06	0.001	44.2	21	4.5
Russia	147.4	32.5	0.73	0.047	22.5	—	—
Slovak Republic	5.4	4.3	0.5	0.46	84	40	4.5
Slovenia	2.0	2.0	0.101	0.433	83.3	13	4.9
South Africa	42.1	25.3	0.42	0.65	59.5	1	5.0
Spain	39.9	25.0	2.0	0.51	66.4	33	5.2
Sweden	8.9	4.6	0.534	0.041	57.3	12	4.0
Switzerland	7.25	3.6	0.72	0.03	59.9	33	4.9
Ukraine	50.5	6.8	0.096	0.06	13.7	36	—
United Kingdom	59.2	56.7	5.9	3.9	99.4	64	4.1
United States	270.3	235.5	19.1	6.5	83.7	10	4.6
Venezuela	23.2	17.8	0.018	0.49	74.3	1	—

Source: Statistical Handbook, Brewers and Licensed Retailers Associatoin, London, 2000.
[a]Includes Luxembourg, because of inaccuracies introduced by crossborder trading.
[b]A dash indicates data not available.

Table 1.3
Growth or Decline in Beer Volume (Million hl) since 1970

Country	*1970*	*1980*	*1990*	*1995*	*1999*
Denmark	7.1	8.2	9.0	10.1	8.0
France	20.3	21.6	21.4	20.6	19.9
Germany	103.7	115.9	120.2	117.4	112.8
Ireland	5.0	6.1	6.4	7.4	8.7
Netherlands	8.7	15.7	20.0	23.1	24.5
United Kingdom	55.1	64.8	61.8	56.8	57.9
South Africa	2.5	8.3	22.6	24.5	25.3[a]
China	1.2	6.0	69.2	154.6	196.4[a]
Japan	30.0	45.5	66.0	67.3	72.2
Korea (Rep)	0.9	5.8	13.0	17.6	14.1[a]
Australia	15.5	19.5	19.4	17.9	17.5[a]
Canada	15.8	21.6	22.6	22.8	22.8[a]
United States	158.0	227.8	238.9	233.7	235.5[a]
Brazil	10.3	29.5	58.0	84.0	88.0[a]
Mexico	14.4	27.3	39.7	44.5	54.8[a]
World	648.1	938.6	1,166.0	1,249.8	1,333.4[a]

Source: Statistical Handbook, Brewers and Licensed Retailers Association, London, 2000.
[a]1998 value.

At the other end of the scale, it is apparent that the brewing industry has suffered in some countries, with a substantial decline in production volumes. Traditional beer-drinking countries such as the United Kingdom, Germany, and Denmark all show a decline. In part this reflects a tightening of the belt of the consumer and perhaps a change in drinking habits, but it is also increasingly recognized that drinking of even moderate amounts of alcohol is unacceptable if one is also to participate in other activities, notably driving. The authorities are particularly vigorous in their monitoring of drunk driving in Australia—being stopped for a "breathalyzer" check there almost seems to be the norm rather than the exception. In the United States, per capita consumption of beer has hovered around 83.5 liters per head since 1995. It had reached a peak of 91.2 liters per head in 1990.

There has been tremendous rationalization in the brewing industry in all countries, with bigger and bigger volumes being concentrated in fewer, larger companies. Already I have mentioned the merger of the Brazilian companies to form AMBEV and the acquisition of Kronenbourg by Scottish & Newcastle, who as recently as 1988 were only the sixth-biggest brewing company in Britain. There have been plenty of other examples. Interbrew, a family-owned concern from Leuven in Belgium and Brewers of a fine lager, Stella Artois, now owns Labatt (Canada), Whitbread (England), and Beck's (Germany), among others. Most recently they acquired the Bass brand from the famed U.K. Brewer, which had decided to focus its interests on hotels and the retail of beer rather than on the brewing of it. The U.K. government is peculiarly obsessed with supposed monopolies; thus Interbrew could not acquire the whole of the Bass company's brand portfolio. Accordingly, Coors stepped in to purchase Carling, the biggest-selling beer in the United Kingdom. Small wonder that the tables depicting the size and shape of the brewing industry rapidly go out of date! Table 1.1 represents a snapshot in time. It seems that hardly a month goes by without a fresh acquisition being made by one or another of these companies. And so, as I write, Scottish & Newcastle have moved in on the Finnish Brewer Hartwall, a company that currently controls half of the strongly growing Russian market. It almost seems as if the Top Ten list of Brewers is just as eagerly contested as the pop music charts or a soccer league table. It was only a matter of time before (antimonopoly laws permitting) there would be mergers among those in the Top Ten, making, perhaps, four mega-Brewers. This process appears to have begun with the acquisition of Miller Brewing Company by South African Breweries.

In truth the drinker is often not quite sure who owns the brand in her glass. In Finland Carlsberg heavily influences the other major brewer, Sinebrychoff, as is the case for two of the three biggest breweries in Sweden. In the Czech Republic, the famed Pilsner Urquell, the original brand of the genre, is owned by South African Breweries. Modelo in Mexico is 50.2% Anheuser-Busch, while FEMSA is 30% Interbrew and 8% Miller. In New Zealand, while 23% of Dominion Breweries is Heineken money, Kirin has a 45% stake in Lion Nathan. In turn, Lion Nathan owns a diversity of breweries in Australia, notably the Perth-based Swan, South Australian in Adelaide, Castlemaine in Brisbane, and Toohey's in Sydney. As this book is completed we find Canada's Molson Breweries purchasing Kaiser, the second biggest Brewer in Brazil, aided by a 20% stake from Heineken.

At the other extreme, there has been a gratifying trend in the establishment of newer, smaller breweries, called either microbreweries or pub breweries, depending on their size. The Institute of Brewing Studies defines a microbrewery as one that produces less than 15,000 barrels of beer each year. A brewpub is classified as an establishment that sells the majority of its beer on site, whereas a contract brewing company is a business that hires another company to produce its beer; a prominent example would be the Boston Beer Company. A regional brewery has a capacity of between 15,000 and 2 million barrels.

In the United States in the 1960s there were fewer than 50 breweries. Now there are more than 1,000—and they're still coming, many with a ca-

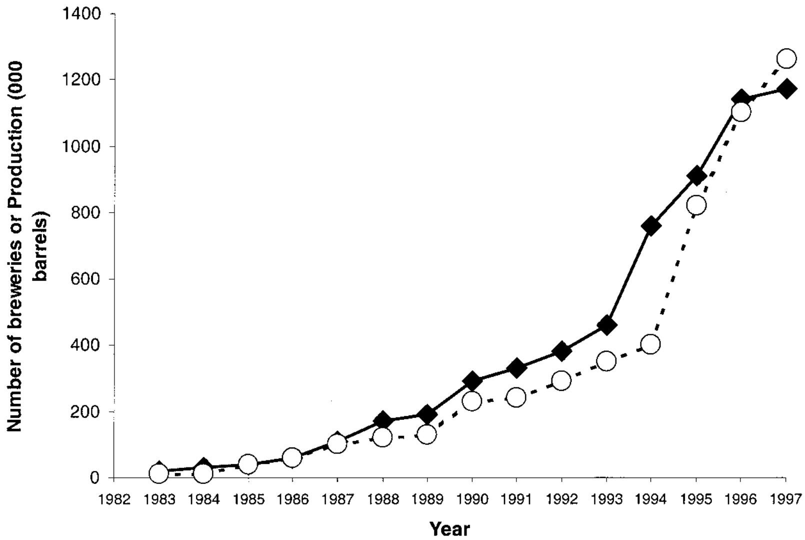


Figure 1.4 *The growth of micro- and pub brewing in the United States. ○ Breweries; ◆ Products*

pacity of just a few barrels. President Jimmy Carter's initiative to allow home brewing in the United States was one significant factor presaging the start of the microbrew surge, as was the entrepreneurial and devoted attention of pioneers such as Fritz Maytag, in his case with the Anchor Brewing Company in San Francisco (see fig. 1.4). The sector generates a healthy consumer interest in beer and in the art of brewing. Whether on street corners, dispensing full-flavored beers of diverse character to accompany good-value meals, or in baseball stadia, adding to the sublime pleasure of the ball game, these tiny breweries greatly enrich the beer-drinking culture. Each year a new group of young hopefuls step into my office expressing their overwhelming desire to open a brewery. A laudable sentiment indeed. My reply to them is invariably that, apart from my class, what they need is a compassionate bank manager and a chef, for let nobody kid themselves: it is the food that pays the bills in a pub brewery more than the beer (see "A Week in the Life of a Small-Scale Brewer"). It is only when a company gets to a size like that of Anchor (more than 100,000 barrels per annum) and, most exceptionally, Sierra Nevada (see "Sierra Nevada") that beer is unequivocally the driving force. Smaller-scale operations are starting and finishing all the time. From 1997 through 2000 the failure rate for brewpubs and microbreweries in the United States averaged out at a little over one in three.

Table 1.2 reveals several more intriguing statistics. For example, the average strength of beer ranges from a high of 5.2% ABV in Belgium, Poland, Portugal, and Spain to a low of 4.0% in Korea, Mexico, New Zealand, and Swe-

A Week in the Life of a Small-Scale Brewer

Chief buyer, brewer, cellarman, deliveryman, engineer, quality assurance manager . . . and odd job man, for good measure. Such, and rather more besides, is life for Frank Commanday (pronounced Command-ay). It has been my privilege to meet innumerable brewers in my career in the industry. Not many have impressed me more than Frank, a man who does not let his fervent passion for the brewing industry get the better of an ingrained and genuine understanding of its essential science and best practice technology. Too often brewers on a small scale appear to get subsumed in their own excessively zealous pursuit of some mystical microbrewed Holy Grail, invariably one that is out of all flavor proportion. How refreshing then to find a "pub brewer" who clearly knows all about balance and volume appeal.

Frank is brewmaster at the E & O Trading Company on Sutter Street in San Francisco. Recently a sign appeared over the sidewalk to announce that there is a brewery within. Prior to this you would have been hard pressed to know that here there was beer brewing. Only by taking a downstairs comfort break in the midst of sampling the restaurant's magnificent South East Asian cuisine would you realize that the fabulous beers on tap were coming direct from serving tanks in a pristine brewery on the premises. The facility is understated: the beers speak for themselves, delightfully complementing the subtle flavors of Indonesian, Chinese, Indian, and diverse other Eastern delicacies. This is not sausage and burger country.

I take one of my classes to see the Commanday operation. It's only by listening to somebody like this that one can really get a feel for the sheer hard work and, to a substantial degree, routine drudgery of life as a one-man brewing show, while savoring the transparent joy that is also to be had from being master of one's own destiny.

Frank was at graduate school at the University of California, Davis, pursuing a master's degree in microbiology, from 1982 to 1985. It was soon after the "big bang" of smaller breweries in California and the Pacific Northwest, with the likes of Red Hook and Grant's in Washington and, in California, New Albion in Mendocino, Sierra Nevada in Chico, and of course Fritz Maytag's Anchor Brewery in San Francisco. Frank Commanday liked what he saw and cut his teeth as a summer cellarman with Sierra Nevada at a time when their brewlength was of the order of 10 barrels. As Frank says, this "primed the pump" of his brewing passion.

Graduating from U.C. Davis, he moved to Oregon with a view to doing doctoral work, but the brewing bug had bitten badly, and he joined Blitz Weinhard's quality assurance lab in Portland. He became the first employee of the Portland Brewing Company, starting off with wielding a sledgehammer as the brewery was constructed. His prior experience at Sierra Nevada and Chico was invaluable in his mission to establish the quality assurance, cleaning, and sanitizing programs at Portland. Two years later he moved on to Widmer Brothers, where in almost a decade he again established a quality assurance program, as well as the company's engineering department. As the company grew and grew ("from baling wire to PLCs"), Commanday came to realize that his real love was the hands-on work. "I needed to forge my identity as a craft brewer. I am not designed—and have no desire—to be a hands-off manager. I need to know how things work. It's so much more fulfilling for me to make or mend something."

Frank stepped out of Widmer to design and teach, at Portland Community College, an introductory course on the brewing industry. Then, in 1997, he joined E & O, and he was excited to be asked to install a brewery to his own specifications and formulate his own brews ("a brewer needs to be his own advocate"). He arrived in April and the tanks were charged with beer for the opening on August 12.

Frank Commanday brews some 600 barrels of beer each year, with a brew length of 10 barrels. All the beer is retailed at either the parent restaurant or its sister in San Jose. Guess who ferries the kegs? "I'm packaging and distribution, sales rep and line cleaner!"

There are five fermenters and five serving tanks. This allows for four standard beers and one seasonal brew. Frank's biggest seller is his I.P.A. There is a pilsner and a stout—close to an Imperial one and nitrogenated. The fourth, and equally popular, is his Eastern Golden Ale, "a beer with training wheels" for the younger drinker, with a low bitterness and seamless and succulent melding of Cascade hops and orange blossom honey. Seasonally there's a spring Bock, a wheat beer in the summer (turbid but not like broth), a brown ale in the fall, and a mildly spiced winter warmer called Dragon's Breath.

Commanday's pragmatism and process awareness means that he successfully produces each of these using a lager-style yeast. He knows full well that horses can take different courses. His awareness of appeal and food complementarity means that he is (gratifyingly) not heavy-handed with his hops.

So how does a week in the life of E & O Trading Company's resident brewmaster unfold?

Monday: "I might wash some kegs and fill them in preparation for taking to San Jose. As I wear overalls, it is generally assumed that I must be the general facilities manager! So I might end up repairing a sump or an errant dishwasher, and much more besides. I'll also find time to check the inventory and do some ordering."

Tuesday: Beer is filtered after the filter has been sterilized and the recipient serving tank cleaned. Generally it's a day for cleaning and hygiene—Frank is a role model for anyone who wants to appreciate the criticality of pristine conditions for the production of excellent beer.

Wednesday: A brewing day. Malt (which is collected from the San Leandro supplier by Frank in his truck) is milled into red plastic tubs and hand-carted to the mash tun for mixing with water by means of a paddle. "There's a lot of schlepping in the brewery," he says. While the mash is progressing, Commanday cleans the fermenter. The brew will have been started at around 1 P.M. so that the boil does not start before 5 P.M., for fear of offending the neighbors with the aromas produced. This means that on brew days he doesn't head home to El Cerrito much before midnight—"but it beats rush hour."

Thursday: Frank filters another batch.

Friday: Brewing again. And the unavoidable management meeting.

So what are the pros and cons in the lonely life of a restaurant brewer? "Best of all is the autonomy. You can make decisions without a 'bean-counter' peering over your shoulder. You have control over the equipment and its layout. But you need to be able to avoid being shoehorned into unacceptable working environments. Real estate is expensive, so there is competition for space (butts on seats) and pressure to keep costs low. I am fortunate in my 'submarine' location in not working in a goldfish bowl. The brewer must fight for the essentials—such as a good floor. But you must also have a firm grasp of how to control your process without the advantage of all the expensive analytical instruments available to the 'big guys.'

"The downside is that nobody else in the company really knows what you do or what your challenges are. You are existing in the restaurant, not the brewing business. As cocktails and wine have a greater profit margin, house-brewed beer doesn't always get the attention it deserves. Another concern is: where do you go to from here? In a large company the sky's the limit. In this type of role one can't expect too large a salary, and you have already reached the pinnacle. Many young brewers aspire to having their own place one day. But they should be aware: they will end up as restaurateurs, not brewers, and they should get as much experience as they can on the floor or waiting at tables. But the really successful restaurateurs appear to be born to it, not to brewing.

"It's a wonderful life, though. But you need passion. Come 5 o'clock you can't simply leave the papers on the desk and turn out the light. There might be a pump to mend!"

Sierra Nevada

Figure 1.5 *Ken Grossman.* *Courtesy of Sierra Nevada Brewing Company.*

Ken Grossman (fig. 1.5) commenced his brewing (as so many folk do) in a bucket at home, in his case in southern California. In 1972 he moved north to study science at Butte College and California State University at Chico. Four years later he opened a small shop in Chico selling home brewing supplies, while daydreaming about opening his own commercial brewery. In 1980 the Sierra Nevada brewery was opened in a small warehouse in the city (fig. 1.6), with converted dairy equipment and a packaging line adjusted from soft drink use. Soon the prizes started accumulating for a series of distinctively hoppy beers, including the flagship Pale Ale. Now, a little more than 20 years later, the company is producing more than 500,000 barrels of beer each year, shipping it to every state, and operating one of the most impressive and delightful breweries to be found anywhere in the world (fig. 1.7).

Figure 1.6 *Where it all started: the Gillman Street brewery of Sierra Nevada.* *Courtesy of Sierra Nevada Brewing Company.*

Figure 1.7 *One of the two brewhouses of Sierra Nevada now.* *Courtesy of Sierra Nevada Brewing Company.*

den. This disguises, of course, a myriad of beer types of diverse strengths, which in the United Kingdom, for instance, range from alcohol-free beers (by law containing less than 0.05% ABV) to the so-called superlagers of 9% alcohol or above. Nonetheless, national preference is reflected in the strengths indicated in table 1.2. People often confuse strength with flavor. Some of the British ales are relatively low in alcohol content, despite their fuller flavor. Those used to drinking them can get a curious surprise after a few beers in, say, the United States, where many of the mainstream beers tend to have substantially more alcohol, if not flavor intensity.

The great beer-exporting countries of the world, with the exception of Germany, feature major brewing companies. The Netherlands, home of Heineken, exports more beer than any other country, some 49% of its production. Denmark, where Carlsberg is based, exports 30% of its beer. Ireland, famed for Guinness ("the black stuff"), exports 41% of its production.

The export of beer first took off with British imperialism in the nineteenth century and with the shipping of vast quantities of so-called India Pale Ale (I.P.A.), a product still available from several Brewers in the "home market" today. This beer was of relatively low strength, to suit drinkability in hotter climes, but was well hopped, as hops have preservative qualities. The advent of pasteurization, and the attendant destruction of potential microbial contaminants, enhanced the market for such exports, as it meant that shelf lives could be lengthened still further.

Beers are still exported from country to country, a principal driving force being the opportunity to make marketing claims concerning the provenance of a product. However, most major Brewers realize how illogical it is to transport vast volumes of liquid across oceans—after all, by far the major component of beer is water! They have either established their own breweries to supply specific market regions or have entered into franchise agreements with Brewers in target countries, who brew their beer for them, generally under extremely tight control. For example, beers from major American Brewers are brewed locally in the United Kingdom, with each of these companies insisting on the adherence to brewing recipes, yeast strain, and the various other features that make their brands distinctive. Companies operating franchise agreements may insist on key technical personnel being stationed in the host brewery in order to maintain responsibility for a brand. A good example would be the presence of a brewer from Kirin at Anheuser-Busch's Los Angeles plant.

There are, of course, circumstances when a franchise brewing approach is impractical and when it is also not possible to ship finished product. For instance, in 1944 HMS *Menestheus* was converted from a minelayer to a floating club and brewery. Seawater was pumped on board and distilled to produce the brewing liquor. Malt extracts and hop concentrates represented transportable ingredients for a nine-day production cycle. The production rate was 1,800 gallons per day for the pleasure of faraway troops.

All Brewers are well aware of the fact that they are in competition not only with one another in the marketplace but also with producers of other drinks, both alcoholic and nonalcoholic. The esteemed drinks analysis company Canadean calls it share of throat. Yet if we look at data (1998) for per capita drinks consumption in the United States in terms of numbers of 8 ounce servings, then beer, at 357, ranks second to soft drinks (861), with coffee (315) and milk (301) some way behind. If you consider that the legal drinking age in this country is 21, it is clear that beer commands a significant position.

For wines and spirits, just as for beers, there are distinct national differences in consumption (table 1.4). In most countries more beer than wine is consumed (although we should remember that wines generally contain two to three times more alcohol than beer, volume for volume). However, the French drink considerably more wine than beer, while in Portugal there is almost an equivalence between the two beverages.

One significant factor influencing the respective amount of beer and wine drunk in different countries is the relative excise tax (duty) raised on them (table 1.5). In seven member states of the European Community (EC), including Italy, wine attracts no duty whatsoever. The tax levy on wine in France is very low, whereas duty rates on wine (but also on other types of alcoholic beverage) are very high in Sweden, Finland, and Ireland.

There are huge differences in the excise rates for beer across the EC. This issue has been brought to the fore in the United Kingdom, in view of the fact that France is nowadays just a 30-minute train ride away through the Channel Tunnel. As beer is so much cheaper in France, because it attracts less than one-seventh of the excise duty levied in the United Kingdom, a growing number of people make trips across the English Channel to buy stocks. Well over a million pints of beer each day are coming across the Channel into England and thence to the rest of the United Kingdom. There are no limitations on the amount of beer you can bring back to the United Kingdom, providing it is for personal consumption, but the retail of such purchases is forbidden. Yet probably half of this imported beer is intended for illegal disposal. From the numbers of vans returning through Kent packed to the roof with beer, it would appear either that there are some fun parties to attend in Britain or the law is being flouted “big-time.” Hundreds of millions of dollars of tax revenue is evaded through smuggling operations into the United Kingdom. It seems unlikely that the duty imbalance will change substantially, particularly as beer duty contributes some two-thirds of the receipts of Her Majesty’s Customs and Excise, and this is matched by the take from value added tax (VAT). No other member state of the European Community collects anywhere near as much revenue from Brewers. France, iron-

Table 1.4
Drinks Consumption (Per Capita, 1998)

Country	*Beer (liters)*	*Wine (liters)*	*Spirits (liters of pure alcohol)*
Australia	95.0 (+0.3)	19.7 (+0.9)	1.4 (+0.1)
Belgium	99.0 (−2.1)	26.7 (+3.0)	1.1 (−0.1)
Brazil	52.9 (−1.3)	1.9 (0)	1.5 (0)
Canada	67.0 (+2.2)	8.9 (+0.4)	1.8 (+0.1)
China	15.6 (+0.6)	0.2 (0)	3.0 (0)
Czech Republic	160.8 (−2.1)	15.4 (0)	3.2 (0)
Denmark	107.7 (−9.0)	29.1 (−0.2)	1.1 (0)
Finland	79.1 (−2.0)	8.3 (+0.4)	1.9 (+0.1)
France	38.6 (+1.6)	60.0 (0)	2.4 (0)
Germany	127.4 (−3.8)	18.1 (−0.1)	1.8 (0)
Republic of Ireland	124.2 (+0.5)	8.8 (+1.8)	1.9 (+0.2)
Italy	26.9 (+1.5)	52.0 (−1.5)	0.5 (0)
Japan	57.2 (−0.3)	3.3 (+1.5)	2.3 (+0.1)
Netherlands	84.3 (−2.1)	18.4 (+0.9)	1.7 (−0.1)
New Zealand	84.7 (+0.1)	17.0 (0)	1.5 (+0.5)
Norway	49.7 (−3.2)	11.0 (+1.7)	1.1 (+0.2)
Portugal	65.3 (+1.7)	58.0 (−1.0)	1.5 (0)
Russia	22.5 (−2.1)	6.0 (+0.1)	6.0 (+0.5)
Slovak Republic	93.8 (+4.2)	15.2 (−0.1)	4.1 (+0.1)
South Africa	59.5 (+5.0)	8.0 (+0.1)	1.0 (−0.1)
Spain	66.4 (−0.2)	35.0 (+4.5)	1.8 (−0.4)
Sweden	57.3 (−4.4)	14.6 (+0.1)	1.1 (0)
United Kingdom	99.4 (−4.2)	17.6 (+0.7)	1.3 (−0.1)
United States	83.7 (+0.5)	7.3 (+0.1)	1.9 (0)

Source: Statistical Handbook, Brewers and Licensed Retailers Association, London, 2000.
Note: Values in parentheses indicate growth or decline on previous year.

ically, is the next biggest drawer on Brewers but levies less than 30% of the tax taken in the United Kingdom, most of that being VAT.

In the United States matters are complicated by three layers of government levying taxes on beer. Congress first placed an excise tax on beer in 1862. The federal rate of excise tax for the large Brewers has been $18 per barrel (U.S.) since it was doubled in 1990 following strong lobbying by anti-alcohol advocates. State excise tax varies tremendously, but the current median is 18.5 cents per gallon. Sales taxes also apply in most states. The lowest rate of taxation is in Wyoming, at 2 cents per gallon, while it is a whopping 92 cents per gallon in Hawaii. Other high rates are in Alabama, North Carolina, South Carolina, Florida, and Georgia, whereas rates are somewhat low in Colorado, Maryland, Missouri, Kentucky, Nevada, Oregon, Pennsylvania,

Table 1.5
Rates of Excise Duty and Value-Added Tax in the European Community

Country	*Beer (cents per pint at 5% ABV)*	*Wine (cents per 75 cl bottle at 11 % ABV)*	*Spirits ($ per 70 cl bottle at 40% ABV)*	*VAT %*
Austria	9.2	0	1.9	20.0
Belgium	10.8	32.6	4.3	21.0
Denmark	24.3	69.3	9.5	25.0
Finland	74.7	162.5	13.0	22.0
France	6.8	2.3	3.7	19.0
Germany	5.0	0	3.4	16.0
Greece	7.7	0	2.3	18.0
Ireland	51.9	188.4	7.1	21.0
Italy	8.9	0	1.7	20.0
Luxembourg	5.0	0	2.7	15.0[a]
Netherlands	11.1	33.6	3.9	17.5
Portugal	7.4	0	5.3	17.0[a]
Spain	4.4	0	1.8	16.0
Sweden	45.6	223.8	15.4	25.0[b]
United Kingdom	50.7	173.7	8.2	17.5

Source: Statistical Handbook, Brewers and Licensed Retailers Association, London 2000.
Note: Original data was quoted in pounds sterling. An exchange rate of £1 = $1.50 has been employed and values rounded to one decimal point. UK pint is used.
[a]VAT rates for wine are lower.
[b]Rate for beer < 2.8% ABV is lower.

Wisconsin, and the District of Columbia. Federal, state, and local taxes on the brewing industry amount to over $45 billion each year.

Although production costs associated with the brewing industry vary enormously from company to company, I would estimate that excise tax probably accounts for approximately 27% of the cost of beer in the United States. Estimates for other expenses would be malt (3.5% of costs), adjuncts (1.5%), hops (0.2%), packaging materials (26%), production costs (20%), and sales costs (21%). Hence excise duty is one of the single most costly elements of a can of beer.

Brewing makes a major economic impact in the United States, amounting to $200 million in sales each year. Apart from the tax contributions, it is a major employer, with over 2.5 million people working either directly in the production, marketing, and selling of the product or indirectly in the industries that supply the Brewers, including farming, malting, and the production of packaging materials. For instance, over 60 billion beer bottles and cans are produced each year.

Table 1.6
Trends in World Beer Production

Year	*World beer production (million hl)*
1970	648.1
1980	938.6
1990	1166.0
1994	1224.9
1995	1249.8
1996	1267.6
1997	1316.8
1998	1333.4
2000	1363.9
2001 (projected)	1404.0
2003 (projected)	1472.2
2006 (projected)	1564.1

Source: Statistical Handbook, Brewers and Licensed Retailers Association, London, 2000, and *Canning and Filling,* January 2002.

Despite the competition beer faces from wine, there has been a steady growth in world beer production in recent years, and this growth is projected to continue (table 1.6). The volume of beer brewed has doubled since 1970, during which time the world population has increased by 59%. As tables 1.3 and 1.4 show, there has been formidable growth in the quantity of beer brewed and consumed in a number of countries. China, in particular, stands out as a country where an increasing number of people in an increasingly favorable economic climate have acquired access to beer, with similar stories having unfolded over recent years in countries in South America and Africa.

Returning to the United States, and before leaving this statistical survey, we might analyze the drinking habits of the individual states of the Union (table 1.7). It seems that the good folk of New Hampshire head up the beer stakes, with Nevada a close second. Utah, unsurprisingly, has the lowest per capita consumption.

With the exception of brewpubs, where the beer is brewed on the premises, it is illegal for a Brewer in the United States to sell directly to the consumer. This is quite unlike the situation in some other countries, where the Brewer to a greater or lesser extent is able to act as seller as well as producer, for example through one's own pub.

After the repeal of Prohibition, the center of gravity on control of beer sales was placed firmly in the 50 states of the Union rather than in the federal government. The upshot of this is that there is a plethora of differences,

Table 1.7
Shipments of Beer in the States, 2000

State	*Estimated population (000)*	*Beer shipments (000 brls)*	*Consumption per capita (liters per head)*
California	34,501	20,550	70
Texas	21,325	17,966	99
New York	19,011	10,164	63
Florida	16,396	12,236	87
Illinois	12,482	9,038	85
Pennsylvania	12,287	8,709	83
Ohio	11,373	8,493	87
Michigan	9,990	6,761	79
New Jersey	8,484	4,673	64
Georgia	8,383	5,711	80
North Carolina	8,186	5,590	80
Virginia	7,187	4,862	79
Massachusetts	6,379	4,166	76
Indiana	6,114	3,954	76
Washington	5,987	3,714	73
Tennessee	5,740	4,001	82
Missouri	5,629	4,333	90
Wisconsin	5,401	4,741	103
Maryland	5,375	3,153	69
Arizona	5,307	4,287	95
Minnesota	4,972	3,588	84
Louisiana	4,465	3,804	100
Alabama	4,464	3,028	79
Colorado	4,417	3,339	88
Kentucky	4,065	2,517	72
South Carolina	4,063	3,358	97
Oregon	3,472	2,391	81
Oklahoma	3,460	2,213	75
Connecticut	3,425	1,854	63
Iowa	2,923	2,299	92
Mississippi	2,858	2,316	95
Kansas	2,694	1,768	77
Arkansas	2,692	1,697	74
Utah	2,269	928	48
Nevada	2,106	2,066	115
New Mexico	1,829	1,575	101
West Virginia	1,801	1,274	83
Nebraska	1,713	1,399	96
Idaho	1,321	846	75
Maine	1,286	882	80
New Hampshire	1,259	1,258	117
Hawaii	1,224	942	90
Rhode Island	1,058	707	78
Montana	904	814	105
Delaware	796	617	91
South Dakota	756	624	97
Alaska	634	463	85
North Dakota	634	572	106
Vermont	613	440	84
D.C.	571	465	95
Wyoming	494	406	96

Source: Beer Institute, Washington D.C. (www.beerinstitute.org) some subtle but some substantial, in the laws governing beer in different locations. One of the most significant comes in Utah, where by law no beer for sale can be in excess of 3.2% alcohol by weight (4% ABV), unless it is retailed in state-owned stores. Some states will allow beers of typical average strength (e.g. 5% ABV) but prohibit the sale of the very strong beers.

In all states there is, by law, a three-tier arrangement comprising the Brewer (supplier), the distributor (wholesaler), and the retailer. The majority of distributors will deal with products from different Brewers. The system hinges on the negotiated contracts drawn up between the various elements of the chain, which will embrace not only cost structures but also quality-related issues such as hygiene standards, age of beer in storage, and so on.

A Brief History of Beer

Since this small book is published in the United States, whose brewing pedigree has British and then German antecedents, I will focus on the history of brewing in the latter two countries, after a brief look at the very roots of beer and before addressing the relatively youthful history of the product stateside.

Ancient Origins

Osiris, the Egyptian god of agriculture, is credited with being the “father” of beer. That, of course, is a matter of faith. With rather more certainty we can say that it was the people who worshiped Osiris who were responsible, while ascribing the fortuitous discovery of fermentation to the divine intervention of their favorite deity. Thus historical accounts of brewing cite ancient Babylon of some 8,000 years ago as being the birthplace of beer (although it has recently been claimed that a forerunner of beer was being brewed in Amazonia some 2,000 years before that). Beer was consumed throughout the Middle East, but, as a drink, it would hardly have borne much resemblance to what most of the world today regards as beer. According to Delwen Samuel, a distinguished researcher at Cambridge University in England,

> beer, together with bread, was the most important item in the diet of the ancient Egyptians. Everyone, from Pharaoh to farmer, drank beer and no meal was complete without it. Beer was much more than just a foodstuff. In a cashless society it was used as a unit of exchange, its value fluctuating just as currencies do today. Furthermore, beer played a central role in religious belief and ritual practice. Offerings to the gods or funerary provisions included beer, either real or magical.[1]

Figure 1.8 *Painted wooden tomb model of a woman straining mash for brewing, with 10 conical beer jars. From Assiut, Middle Egypt, c. 2000 B.C. British Museum, EA 45196. (Copyright: The British Museum.)*

Samuel's archaeological pursuits have unveiled the remains of beer solids crusted to the inside of ancient vessels, and among these solids were found fragments of grain. She has painstakingly examined these remains, using techniques such as scanning electron microscopy, and has made proposals as to how beer was brewed in Egypt 3,000 years ago from malted barley and a primitive type of wheat called emmer (fig. 1.8). The recipe was used by the Brewers Scottish & Newcastle to make 1,000 bottles of a beer they called Tutankhamun Ale—and it sold out from the prestigious Harrods store in Knightsbridge, London, in three weeks.

The techniques applied in the brewing of beer by the Egyptians seem to have been quite refined. Exactly how the first beer was developed several thousand years prior to this is unclear, but it might be anticipated that its origins were founded on serendipity and were linked to the baking of bread. Most commentators suggest that batches of barley must have gotten wet through inadequate storage (rain was more plentiful thereabouts than it is now) and, as a result, started to germinate. Presumably, it was found that drying stopped this germination, and, logically, people would have discovered that this "cooking" improved the taste of the grain. Nor would it have taken them long to realize that malt is more nutritionally advantageous than raw barley: those eating malt would have been healthier than those whose diet included barley and, for certain, would have found their meals to be tastier.

It is supposed that the sprouted barley (forerunner to today's malt) was made into a dough before bread making, and then batches of the dough spontaneously fermented through the action of yeasts living on the grain and in cracks and crevices in vessels. Soon the ancient brewers would have realized that the dough could be thinned with water and strained as a precursor to fermentation and that the process could be accelerated by the addition of a proportion of the previous "brew." A range of plants would have been used to impart flavors, among them the mandrake, which has a flavor much like leek. The use of hops came much, much later.

The work of archaeologists has suggested that in Mesopotamia and Egypt the characteristic tool of the brewer was an earthen vat. Certainly hieroglyphics depict people stooped over such vessels in pursuit of their craft. It has been suggested that the pharaoh Rameses had a brewery that furnished 10,000 hectoliters of beer each year free of charge to those employed in the temple. Beer was staple stuff: the Code of Hammurabi, 1,800 years before the birth of Christ, decreed that those overcharging customers for their beer were to be drowned.

It has even been claimed that modern civilization has its origins in the brewing of beer and that the urge to domesticate barley and cultivate it in a controlled manner for the production of beer was the justification for our ancient forebears settling in communities rather than pursuing a nomadic existence.

The Egyptians passed on their brewery techniques to the Greeks and Romans. However, in ancient Greece and Rome wine was the drink of the privileged classes; beer was consumed by the rest. Beer was not foremost among the developments bestowed by the Romans in the lands they conquered. Pliny the Elder (A.D. 23–79), a Roman author, was almost contemptuous in his view that "the whole world is addicted to drunkenness; the perverted ingenuity of man has given even to water the power of intoxicating where wine is not procurable. Western nations intoxicate themselves by means of moistened grain."

It seems that it was through a more northerly route that the Celts brought westward their ability to brew. Perhaps this related to the mastery over wood of the people of northern and central Europe and their ability to fashion it into brewing vessels and barrels. Whereas the Greeks and others in the South were drinking wine from pottery, the German tribes were drinking barley- or wheat-based drinks out of wood. Pliny encountered *cerevisia* in Gaul and *ceria (ceres)* in Spain; thus brewing yeast was named *Saccharomyces cerevisiae*.

In the first century A.D. there is mention of Britons and Hiberni (Irish) making *courni* from barley, which had probably been cultivated in England since 3000 B.C. The ancient name for ale was *coirm*.

For the Danes and the Anglo-Saxons, ale had been a favorite beverage, for grapes could not be readily cultivated in the colder northern climes. Beer was deemed the perfect beverage of heroes, and Norse seafarers were fortified in battle by the thought that, should they perish, they would go to drink ale in Valhalla. The Vikings had a verse about drinking heartily before putting out to sea next day, hence the origin of the phrase "three sheets to the wind." The Scandinavian word *bjor* became *beer* for the Anglo-Saxons.

Britain Basically

The manner by which the ancient Britons produced their beer is not entirely unrecognizable: "the grain was steeped in water and made to germinate, by which its spirits were excited and set at liberty; it was then dried and ground, after which it was infused in a certain quantity of water and, being fermented, it became a pleasant, warming, strengthening and intoxicating beverage."

Much of the history of the world's brewing industry is tied up with the church, to the extent that the monks in the Middle Ages were even convinced that the mortar used in the building of their churches and monasteries was better if mixed using ale rather than water. To this day, the strong Trappist beers of Belgium are brewed by monks, and bona fide travelers in England are still entitled to lay claim to ale and bread if they care to visit a cathedral church. The Domesday Book (1086) records that the monks of St. Paul's Cathedral in London brewed almost 70,000 gallons (U.K.) of ale that year. Monks used the symbols X, XX, and XXX as symbols for level of quality.

Ale was exceedingly popular. William of Malmesbury said of the British in the early twelfth century: "Drinking was a universal practice, in which occupation they passed entire nights as well as days. They consumed their whole substance in mean and despicable houses; unlike the Normans and French who in noble and splendid mansions lived with frugality. They were accustomed to . . . drink till they were sick. These latter qualities they imparted to their conquerors." The monasteries passed on their skills to those brewing in their own homes. By the Middle Ages ale had become the drink of choice for breakfast, dinner, and supper. Tea and coffee, of course, hadn't arrived.

Out of domestic brewing developed the forerunner of the "brewpub," with beer brewed in the back and sold out front. The two main products were those fermented from the first strainings from the mash tun (strong beer) and those derived from the weaker later runnings (small beer). Brewing was in wooden vessels, except for an open copper for boiling the wort.

Through the Assize of Ale in 1266, ale-conners were appointed in boroughs and cities to test the quality of the ale and the accuracy of the measures being used. Licenses to brew were needed as early as 1305. The ale-conner wore leather breeches and would arrive at the brewery uninvited, pour a glass of ale onto a wooden bench, and sit for 30 minutes. He would chat and drink but otherwise remain static. Woe betides if he stuck to the seat because of sugar left unfermented in the ale.

The brewer had to put out a pole, with bush or ivy plant attached, to register that the beer was ready. Later this became a metal hoop, and various things were displayed in it to differentiate breweries. At first these were the actual objects, for example crossed keys, and hence would the drinking house in that case be recognized as the Cross Keys. Later real objects were replaced by paintings, allowing for more than one pub to be called the King's Head!

By the early fourteenth century there was one "brewpub" for every 12 people in England. The beer was brewed by women (*brewsters* or *alewives*). A *hukster* was a woman who retailed ale purchased from a manufacturing ("common") brewer, while women who sold wine were called *hostesses*.

It was frequent practice to spice ale, by adding pepper or other stimulants, to give the product an additional bite, but for a long time these flavorants did not include hops. Hops for brewing may have been first brought to the United Kingdom to satisfy retainers of Phillipa of Hainault, the wife of Edward III, or by Germans to gratify the German mercenaries supplementing the British army. The cultivation of hops in the Hallertau region of Germany is first recorded in 736, and St. Hildegarde, writing in 1079, is perhaps the first to have mentioned the preservative properties of this plant. It has been claimed that hops were cultivated in Kent by 1463, while some insist that the first reference to hops in England is in a document from 622 by Abbot Adalhard of Corvey. The exact provenance of the arrival of hops is, then, uncertain, but there are several versions of one particular rhyme:

> Hops and turkies, carps and beer
> Came to England all in a year

and

> Turkeys, carps, hops, piccarel and beer
> Came into England all in one year

or

> Hops, reformation, bays and beer
> Came into England all in one year

Prior to the arrival of hops, ale had sometimes been preserved with ground ivy. There was a very clear distinction in the fifteenth century between brewers of ale and beer. In those times the term "ale" strictly described an unhopped product, whereas beer was hopped. We British have always been a tad xenophobic, and thus for 150 years beer brewing was deemed the domain of "foreigners," and ale brewers never passed up a chance to persecute them and rubbish their products. During the reign of Henry VIII, one owner of an ale brewery successfully fetched an action against his brewer for putting in "a certain weed called a hop." It was decreed that neither hops nor brimstone were to be put into ale. We can be thankful that hops gained ascendancy, for they seem infinitely preferable to the materials that were sometimes employed, such as wormwood, gentian, chicory, or strychnia.

By 1576 beer was so prized over ale that Henri Denham, writing in *A Perfite Platforme of a Hoppe Garden,* said:

> Whereas you cannot make above 8 or 9 gallons of indifferent ale out of one bushell of mault, you may draw 18 or 20 gallons of very good Beere, neither is the Hoppe more profitable to enlarge the quantity of your drinke than necessary to prolong the continuance thereof. For if your ale may endure a fortnight, your Beere through the benefit of the Hoppe shall continue a moneth, and what grace it yieldeth to the teaste, all men may judge that have sense in their mouths—here in our country ale giveth place unto Beere, and most part of our countrymen do abhore and abandon ale as a lothsome drink.

Gerard, writing in 1596, was of the opinion that "the manifold virtues in hops do manifestly argue the wholesomeness of beere above ale, for the hops rather make it a physical drink, to keep the body in health, than an ordinary drink for the quenching of our thirste." An early attempt to position beer on a health-positive platform.

By the middle of the nineteenth century, almost 22,000 tons of hops were grown in England, and it was referred to as the "English Narcotic" because it surpassed tobacco in amounts consumed at the time.

Henry VI had appointed surveyors and correctors of beer brewers, whose principles of operation were laudable: "both the malt and hops whereof beer is made must be perfect, sound and sweet, the malt of good sound corn—to wit, of pure barley and wheat—not too dry, nor rotten, nor full of worms, called wifles, and the hops neither rotten nor old. The beer may not leave the brewery for eight days after brewing, when officials should test it to see that it is sufficiently boiled, contained enough hops and is not sweet."

The reader should realize, then, that brewing has a long tradition of high standards. The longevity of the process and the fact that the unit stages of brewing have remained essentially unchanged for hundreds (if not thousands) of years is apparent from this description of a brewery from 1486: "one London brewery included a copper brewing-kettle, a mashvat with a loose bottom and a tap through of lead, a vat and two kettles for wort, two leaded systems for 'licuor,' twenty little tubs for yeast, a fan for cooling the wort, a malt mill, twenty four kilderkins and a beer dray with two pairs of wheels." A government act of 1604 required parish constables to inspect alehouses to ensure that they were operated properly. (William Shakespeare's father was an ale taster in Stratford-upon-Avon prior to this time.) It was emphasized that "the ancient, true and principal use of such places was for the relief of wayfaring men and women and also to fulfil the requirements of those people unable to store victuals in large quantities and not for the entertainment of lewd and idle people." No workman was allowed to spend longer than one hour in an inn unless occupation or residence compelled him so to do. Yet by the reign of Elizabeth I it was reported that in my native Lancashire the alehouses were so crowded on a Sunday that there was nobody left in the church but the curate and his clerk.

By 1688 more than 12 million barrels of beer were being drunk in a year in Great Britain, by a population of 5 million. Even infants, who drank small beer, scarcely ever drank water.

It didn't take terribly long for those in authority to realize that good steady income was to be had by taxing brewers. In 1614 James I had levied 4 pence per quarter of malt, while the Parliamentarians, not noted drinkers and certainly in need of revenue, imposed a duty of 2 shillings per barrel on beer retailing in excess of 6 shillings. Additional duty was placed on malt from 1697 and on hops from 1711. The first laws were already in place in various regions to reduce habitual drunkenness: these included fixed hours of closing at night, Sunday closing, and a requirement that no drinker stayed longer than an hour at a time.

There were three main categories of beer: ale (strong), beer (weak), and the better-quality "two-penny." There were brown, pale, and amber versions of each. People usually asked for "half and half"—equal measures of ale and beer—or "two thirds" ("three threads") : ale, beer, and "tuppenny." (By now the word "ale" was being used synonymously with beer.) In 1722 a London brewer called Ralph Harwood conceived of a product analogous to two thirds, in which the three beers were premixed in the brewery, thereby saving the landlord's and the customers' time. Because most of the customers were porters in the local markets it became known as *porter.* It is now believed that this is too fanciful a story for how this beer style evolved. Whatever the true heritage, within a century the growth of porter had subsided and paler products had gained the ascendancy.

British beer was becoming popular around the world: it was being delivered to ports far and wide by proud ship captains. The Trent Navigation

Act early in the eighteenth century opened up transport from Burton-on-Trent through Hull to the world—enabling the likes of Allsopp and Bass to become household names far from home base. Peter the Great and Catherine the Great in Russia were said to relish the ales shipped to St. Petersburg.

Yet in the early eighteenth-century London gin was gaining in popularity. In 1714 there were 2 million gin distilleries in England, and 21 years later 5 million. A license was needed for selling beer but not gin. Hogarth's paintings capture the scene: in Beer Street people were jolly and healthy, whereas in Gin Street they were debauched.

Benjamin Franklin wrote of the drinking habits of employees in the British printing industry: a pint before breakfast, another with breakfast, a pint between breakfast and dinner, one more at dinner, a pint at 6 o'clock and a last one at knocking-off time. Then it was time to go out and enjoy oneself, presumably down at the pub.

Drunkenness was rife—and the landlord would caution his rowdy customers to "mind their pints and quarts," soon abbreviated to "p's and q's."

Toward the end of the eighteenth century, the impact of taxation and increasing imports of tea and coffee saw a change in domestic drinking habits—tea instead of ale for breakfast.

In the late 1700s, there was a decline in beer brewed at home, reflecting the growth in towns and industry and the increase in proportions of people working in factories. The development of roads and railways allowed big Brewers to distribute their products. By 1815 Barclay Perkins was brewing over 300,000 barrels of beer a year in London, using the latest steam engines, invented by Trevithick and Watt, which facilitated the Industrial Revolution.

There were separate rates of excise for strong beer and small beer. Disputes as to whether a beer was one or the other were settled by dipping a finger, before John Richardson constructed the first brewer's saccharometer in 1784. Another English brewer, Michael Combrune, had 22 years earlier been the first to apply the thermometer in the control of a brewery's operations. Before that time it had been standard practice to poke one's thumb into the boiled wort to ensure that it wasn't too hot to accommodate the yeast—the "rule of thumb."

In the late eighteenth century, the tied house system was started in Britain, in which major production Brewers sold their products through their own wholly owned pubs. By 1810 there were 48,000 alehouses for some 8 million people. Captains of the booming Industrial Revolution were concerned about wages being "wasted" on excess drinking. As a result pubs were limited to strict opening hours, which have been relaxed only very recently. The first teetotal pledge was signed in Preston in 1832.

In the nineteenth century an impressive selection of beers was available to the English consumer. In 1843 Burton Ale had Original Extracts between

Table 1.8
Beer Statistics, United Kingdom

Year	*Population (millions)*[a]	*Beer production (millions of hl)*	*Average strength (°P)*	*Per capita consumption*[b] *(liters/head)*
1899[c]	40.8	60.7	13.73	148.8
1909[c]	44.5	56.2	13.33	126.3
1920[c]	43.7	57.3	9.85	131.1
1929	45.6	40.2	10.73	88.2
1939	47.8 (78)	40.3	10.23	84.3
1949	50.3 (77.9)	43.4	8.35	86.3
1959	52.0 (76.7)	38.9	9.38	74.8
1969	55.5 (75.9)	51.6	9.28	93.0
1979	56.2 (78.6)	66.4	9.4	118.1
1989	57.4 (81)	61.6	9.55	107.3
1999	59.5[d] (80.8)	56.6	9.63[e]	95.1

Source: Based on data in *Statistical Handbook,* Brewers and Licensed Retailers Association, London, 2000.
[a]Values in parentheses indicated percentage of population over the age of 15.
[b]Computed on basis of domestic production–ignores imports and exports.
[c]Includes Republic of Ireland.
[d]Estimated.
[e]Estimated–since 1993 beer strength in the United Kingdom has been declared on the basis of percent alcohol by volume (ABV) rather than as original gravity.

19.25°P (Plato) and 30°P, while common ale was 18.25°P and porter 12.5°P. (As a rule of thumb—to use a phrase just encountered—a beer with an original extract of 10°P will give beer of 4% alcohol by volume. So one of 30°P, if fermented to the same extent [yes, to the same degree] would give a mighty 12% ABV.) Significant quantities of sugar were now being used, which would facilitate these higher gravities. By 1880 the average original extract was 14.25°P, and in 1905 it was 13.25°P (see table 1.8). There were some legendary brewing names in the British Isles, immortalized in the verse of C. S. Calverley:

> O Beer! O Hodgson, Guinness, Allsopp, Bass!
> Names that should be on every infant's tongue!

The Great War highlighted concerns about excessive drinking. Lloyd George ranted that "drink is doing us more damage in the war than all the German submarines put together." War also has implications for technical issues. For instance, in World War II the public wanted volume and were prepared to compromise on strength, and restrictions on the availability of raw materials therefore meant that beer became weaker, the average original gravity now being 10°P. All sides suffered. Brewing of beer in Germany was stopped by decree of the Nazi government on March 15, 1943. The effect on morale must have been substantial. It is claimed that it was at this stage that Hitler gave up personal abstemiousness and began to drink champagne. Strong voices in the U.K. government wanted a ban on alcohol, to divert raw materials to food production. However, a calculation showed that if the beer supply was cut in half and the barley saved was diverted to chickens, then the net benefit would have been one egg per month per person in the ration—and severe public discontent.

The U.S. government offered this advice in a booklet for their servicemen stationed in the United Kingdom: "the usual British drink is beer, which is not an imitation of German beer, but ale. The British . . . can hold it. Beer is now below peacetime strength, but can still make a man's tongue wag." Such advice denied the fact that British ale tends to be relatively low in alcohol, if substantial in flavor. One thing that the North American servicemen would certainly have noticed was the low carbonation of the local ales. The Canadian servicemen in the United Kingdom added salt to their beer, claiming it gave "sparkle" and a good appetizing head.

Germanic Roots

The western brewing industry first became established in the regions of Bohemia (now the Czech Republic) and Bavaria. There were brewers at the Court of Charlemagne who, like Henry VI of England, insisted on wholesome technology in the production of beer. Up to 500 monasteries at the time were brewing beer, especially the Benedictines.

The importance of good malt to good beer was realized, leading to the development of specialist malthouses. The appreciation of hops came earlier in Germany than it did in England, but there were still plenty of adherents to the merits of gruit (the proprietary blend of herbs and spices used to flavor ale), including the archbishop of Cologne, who had something of a monopoly on the concoction.

It is a myth that lager-style products have always been the characteristic beer of Germany. Until the sixteenth century (and not terribly long before the Pilgrim Fathers made their way from England to the New World) ale was the main type of beer in Germany. Bottom fermentation probably started in Bavarian monasteries and was first mentioned in minutes of the Munich town council in 1420. One of the main driving forces for the development of this type of beer was an edict of Prince Maximilian I in 1533 that basically precluded brewing in the summer without a special dispensation. The ale-type products from top fermentation had been brewed in those warmer summer months, but now the emphasis shifted to the bottom-fermentation practices used in the winter, producing beer in sufficient quantities to store ("lager") until the subsequent fall, when brewing could start again.

Perhaps the most durable edict was that of 1516 in Bavaria, when the dukes Wilhelm IV and Ludwig X declared the Reinheitsgebot in an attempt to ensure that undesirable materials did not find their way into the brew. The law survives to this day, extended throughout Germany for domestic brews, restricting the raw materials to malt, hops, yeast, and water. As originally conceived, of course, the law did not include yeast, as it hadn't been discovered yet. (And read on to see what a prominent German chemist was saying about the existence of that beast as recently as the early to mid–nineteenth century.)

A Brave New World

It was the English who brought beer to North America. Sir Walter Raleigh's colonists are said to have malted corn in what is now North Carolina in 1587 (and in South America malted corn had been fermented by the Incas many years before Spanish settlers founded a brewery near Mexico City in the mid-sixteenth century), but it was the Pilgrim Fathers in December 1620 who shipped the first beer into the country. And why did they land at Plymouth Rock? Because "we could no longer take time for further search or consideration, our victuals being much spent, especially our beer." In fact the passengers were urged to take to the shore rapidly, so as to leave what remaining ale there was for the sailors.

Adrian Block, a Dutchman, opened the first brewery in North America, in 1613. It was little more than a log hut in New Amsterdam (which would become New York City). The Dutch West India Company opened the first public brewery in the United States in Manhattan in 1632, with a grist largely of oats. Although the early immigrants were of a somewhat puritanical persuasion, beer was considered (as it still should be) a drink of moderation and certainly preferable to the dubious alternatives then available, which were made by the distillation of fermented corn.

It has been claimed that advertisements were soon being placed in London newspapers inviting experienced brewers to immigrate to America. And the first paved street in America was laid in New Amsterdam in 1657 to aid the passage of horse-drawn beer wagons that hitherto had tended to get stuck in the mud. In 1664 King Charles II seized the former Dutch territory of New Amsterdam and set it in the charge of the duke of York. That "grand old man" certainly had the right idea about properly trained brewers (a legacy continuing to this day and for which I am truly grateful). For it was he

Table 1.9
The Ten Largest Brewing Companies in United States, 1895

Name	*Location*
Pabst	Milwaukee
Anheuser-Busch	St. Louis
Joseph Schlitz	Milwaukee
George Ehret	New York
Ballantine	Newark, NJ
Bernheimer & Schmid	New York
Val Blatz	Milwaukee
William J Lemp	St. Louis
Conrad Seipp	Chicago
Frank Jones	Portsmouth, NH

Source: Courtesy of Dr. W. J. Vollmar.

who proclaimed the Duke's Laws, requiring that brewing should be carried out by people who were trained and qualified so to do.

The Scottish and Irish immigrants brought with them a passion for whisky, which in due course overtook beer as the alcoholic beverage of choice, such that just prior to the Civil War beer was accounting for not much more than 10% of all the alcohol consumed in this nation.

By the eighteenth century, New York and Philadelphia were the principal seats of brewing, and at the turn of the next century, there were over 150 breweries in the United States, with one third of them in each of the same two states. Production, though, was less than 230,000 barrels (U.S.). George Washington had recently died (not before having called for a banning of imports of beer from England to further help the cause of untaxed local brews), leaving his own brewery at Mount Vernon in Virginia. Earlier, in the War of Independence, American troops each received a quart (2 pints) of beer per day. For that luxury the soldiers had perhaps to thank Samuel Adams, the Massachusetts-based leader of the early independence movement, who was himself a brewer. Boston *Tea* Party, indeed! Thomas Jefferson composed the Declaration of Independence at the Indian Queen Tavern in Philadelphia, but history does not record what he had in his glass.

We must move on to the early to mid–nineteenth century, though, to find the beginnings of the great brewing dynasties of the States (table 1.9). Their origins were in Germany. The founding of America's longest-standing brewery, in Pennsylvania, by David Yuengling came in 1829. Frederick and Maximillian Schaefer arrived on these shores in 1838 with a dollar in their pockets but with the drive that enabled them to start a brewery on Fifty-first Street and Park Avenue in New York four years later. In 1840 J. Adam Lemp in St. Louis and John Wagner in Philadelphia opened breweries for the first commercial production of lager-style beer in America, albeit on a modest scale of just 100 barrels and 10 barrels, respectively, in the first year. It was George Manger, using some of Wagner's yeast, who established Philadelphia's first sizeable lager brewery. Soon most of the urban developments sported their own lager breweries. Some great names emerged (see table 1.9 and "Anheuser-Busch," "Frederick Miller," and "Coors"). In 1844 Jacob Best founded the company that would become Pabst, thanks to the wedding of Best's daughter to a steamboat captain, Frederick Pabst. Bernard Stroh, from a Rhineland family with two centuries of brewing pedigree, opened his brewery in Detroit in 1850. Five years later, Frederick Miller bought out Jacob Best's sons' Plank Road Brewery in Milwaukee. In 1860, Eberhard Anheuser purchased a struggling St. Louis brewery and, after his daughter married a supplier named Adolphus Busch, an émigré from Mainz, the mighty Anheuser-Busch Company was born. A dozen years later, another migrant from the Rhineland, Adolph Coors, set up shop in Colorado.

By 1873 there were more than 4,000 breweries in the United States, their outputs averaging some 2,800 barrels each per year. In all countries, brewing undergoes rationalization, so by the end of World War I there were half as many breweries, each producing on average 20 times more beer than 45 years earlier. By the time World War II had run its course, there were just 465 breweries in the United States, their output averaging some 190,000 barrels. Compare those volumes with the output of the gigantic Coors' brewery in Golden, Colorado, which now produces well over 20 million barrels of beer each year. (See table 1.10 for changes in the industry in the latter half of the twentieth century.)

The production of lager (a style that the likes of Busch, Miller, Stroh, and Coors would have been more familiar with in their homeland) demanded ice. Accordingly, such beer had to be brewed in winter for storage (*lagering*) until the greater summer demand. Such protocols were possible in Milwaukee using the ice from Lake Michigan and local caves for storing the beer. Milwaukee rapidly emerged as the great brewing center of the states, with Pabst and Schlitz among those competing with Miller. Once machines were developed to produce ice, then lager could be brewed any time—and anywhere. And the application of Pasteur's proposals for heat-treating beer to kill off spoilage organisms and the advent of bottle and stopper technology meant that beer could be packaged for home consumption and consumed almost anyplace, after shipment nationwide on the burgeoning rail network in railcars that were developed with the latest refrigeration technology. Such developments—as well as the advent of cans, with their lighter weight

Anheuser-Busch

The story of the world's largest Brewer really begins in 1860, when 55-year-old Eberhard Anheuser bought the Bavarian Brewery in St. Louis from George Schneider. There were 40 breweries in the great Missouri city at the time: Anheuser's ranked 29th. A year later, Eberhard's daughter Lilly married Adolphus Busch, who had been born in 1839 in Germany, the second-youngest of 22 children; three years after the marriage, he joined his father-in-law's company.

By now output was 8,000 barrels a year. In 1876 a new brand was developed by Busch with the assistance of his friend the St. Louis winemaker and restaurateur Carl Conrad: a beer that would satisfy all beer drinkers and be of uniform quality wherever it was consumed. The name Budweiser was selected to recognize the Germanic "credentials" of the product yet to be readily pronounceable by everyone. Busch brewed the product, and Conrad bottled and distributed it. In the first year over 225,000 bottles were sold, and within four years volumes had reached 2.3 million bottles. It would, of course, go on to become the world's bestselling beer, with some 54 million hectoliters consumed globally in 1998.

After Eberhard Anheuser died, just four years later, Adolphus Busch (fig. 1.9) became president of the new Anheuser-Busch. He didn't give business acquaintances his card but a pocketknife with a peephole revealing his photograph. Adolphus Busch was the first brewer to recognize how advances in technology were changing and would continue to change American society. The company pioneered the application of the latest developments, such as pasteurization and artificial refrigeration (in the brewing process and also in railcars used to transport the product), in so doing allowing the huge increase in output and the opening up of a vast hinterland for the sale of the beer, wherever the expanding railroads were headed. In 1896 he established another great brand, Michelob, and by 1901 Anheuser-Busch was brewing more than 1 million barrels of beer per annum. Before Prohibition the company was shipping the product to 44 countries on six continents; nonetheless, Busch foresaw Prohibition and had already developed a nonalcoholic beverage when it was imposed.

Figure 1.9 *Adolphus Busch (1839–1913). Courtesy of Anheuser-Busch, Inc.*

Figure 1.10 *Ginger ale from the prohibition years. Courtesy of the Beer History Society (beerhistory.com).*

Adolphus Busch died in 1913, and the presidency of the company passed to August Busch Sr. (born December 29, 1865), on whom it fell to guide the company through the years of Prohibition. The company made truck bodies, refrigerated cabinets, barley malt syrup, ice cream, ginger ale (see fig. 1.10), root beer, chocolate drinks, grape beverages, corn syrup, and baker's yeast. Most famous of all was the nonalcoholic Bevo, which sold as many as 5 million cases one year in more than 20 countries. Upon the repeal of Prohibition, a team of Clydesdales was presented to August by his son, and these animals have been integrally associated with the company ever since. Adolphus Busch III took the company reins in 1934, and his tenure coincided with another great challenge, World War II. War bond purchases by Anheuser-Busch employees footed the bill for two B-17 bombers, one of which was called the *Buschwacker.* The market in the western states was sacrificed in order to free up trains for military shipments. Nonetheless, Adolphus III presided over a tripling of the company's beer output, at least in part a benefit of the advent of canning. One year after the end of the war, the presidency passed to August Busch Jr. (born March 28, 1899). In his case the magnitude of the company's growth was phenomenal, with volumes going from 3 to 34 million barrels. Apart from his enthusiasm for the Clydesdales and the Cardinals baseball team, operating out of Busch Stadium in St. Louis, August Jr. also diversified the company into theme parks, with Busch Gardens. His son August A. Busch III (born June 16, 1937) became president in 1975 and has driven the company to unprecedented heights as the world's leading Brewer and probably the most quality conscious, with brewing operations across the globe. Among the product triumphs has been Bud Light, launched in 1982 and now overtaking even Bud in popularity.

August A. Busch IV runs the marketing wing of Anheuser-Busch, Inc., so the great brewing family tradition continues. In the United States, Anheuser-Busch has breweries in Fairfield and Los Angeles, California, Fort Collins, Colorado, Houston, Texas, St. Louis, Missouri (fig. 1.11), Columbus, Ohio, Cartersville, Georgia, Jacksonville, Florida, Baldwinsville, New York, Merrimack, New Hampshire, Newark, New Jersey, and Williamsburg, Virginia. Its brands are brewed the world over.

Figure 1.11 *The Anheuser-Busch brewery in St. Louis. (Top) 1883. (Bottom) Late twentieth century.*
Courtesy of Anheuser-Busch, Inc.

Frederick Miller

Figure 1.12 *Frederick Miller (1824–1888). Courtesy of the Beer History Society (beerhistory.com).*

Frederick Edward John Miller (fig. 1.12) was born on November 24, 1824, into a wealthy family in Riedlingen, Germany. From age seven to fourteen, he studied in France; then, prior to returning to Germany, he visited an uncle in Nancy. That uncle, fortuitously, was a brewer, and Frederick liked what he saw so much that he decided to stay and learn the trade. Soon he was in a position to brew his own beers, so he leased the royal brewery in Sigmaringen, back in his home country. With the Germanic Confederation of states in some turmoil, Miller became one of many to seek a new life in the United States of America, where he arrived in 1854 with his young wife, Josephine, and their infant son, Joseph Edward. They had in their possession $9,000 worth of gold.

The Millers spent a year in New York before settling in Milwaukee. Before long, Frederick had bought the Plank-Road Brewery from Frederick Charles Best (from the family that developed the Pabst brand) for $8,000. Beer at the time retailed at less than 5 cents a glass in the taverns of Milwaukee. In the first year after Miller bought the brewery, it produced 300 barrels of lager-style beer. By the time he died in 1888, the annual production was 80,000 barrels.

Miller clearly knew his business. The brewery in the Menomonee Valley had a good water supply and ready access to excellent barley grown locally. He was a kindly employer; he opened a boarding house next to the brewery for unmarried staff and, in addition to free meals (four per day) and lodging, paid them salaries of up to $1300 a year.

Sadly for such a generous man, Frederick Miller had quite a tragic domestic life. Josephine died in April 1860, having borne six children, most of whom did not survive beyond infancy. Miller married Lisette Gross the same year, and they had many children, of which only five survived beyond their fledgling years.

It was these children who carried forward the name of the Miller Brewing Company, notable among them being Frederick C. Miller, the grandson of the founder and a Notre Dame football star in his college days. In 1954 Miller was the ninth-biggest brewing company in the United States with production of 2 million barrels. In 1969 Philip Morris Company acquired a 53% controlling share in the company, buying the remaining shares a year later. In 20 years production increased eightfold, making Miller Brewing Company today the second largest Brewer in the United States, a situation that was retrenched in 1999 when it and Pabst each acquired parts of the Stroh brewing empire, as the latter company sadly exited brewing after some 150 years. The relentless march of Brewer nationalization found Miller acquired by South African Breweries in May 2002 for $5 billion.

Coors

Figure 1.13 *Adolph Coors (1847–1929). Courtesy of the Beer History Society (beerhistory.com).*

Adolph Coors Company, the third largest Brewer in the United States, is another founded on German brewing traditions. Adolph Coors (fig. 1.13) founded his brewery in the foothills of the Rocky Mountains at Golden, some 20 miles west of Denver, in 1873. Like Anheuser-Busch, Coors is still characterized by strong family involvement. William K. Coors is chairman of the company, and Peter H. Coors is vice-chairman and chief executive officer of the brewing subsidiary (Coors Brewing Company). For a long time Coors beer held a certain mystique in some states where it was unavailable; until comparatively recently it was shipped to only 11 western states.

The Coors operation differs from that of the other big Brewers in the United States in that it is concentrated on just two sites, the enormous Golden plant, where Adolph Coors first brewed 124 years ago, and, since only 1990, a brewery in Memphis (Tennessee). For 10 years Coors has packaged its product at Elkton, in the Shenandoah Valley in Virginia; the beer is shipped there from Golden in refrigerated tanks on rail cars. In the past few years Coors has moved out of a substantial interest in a brewery in South Korea but has acquired a hefty slice of the old Bass brewing empire, together with the biggest-selling brand in the United Kingdom, Carling Black Label. Incidentally, if you travel widely you will find that this brand is very different in the United Kingdom and in South Africa. The brand originated in Canada, but the rights to it are owned separately by (now) Coors and by South African Breweries. The latter company has very much changed the recipe from the original.

Another unique feature of Coors has been its vertical integration. Although it has relaxed this to a certain extent recently, Coors has long been substantially self-contained: breeding its own barleys, supplying its own malt, making its own cans, supplying its own energy resources, and so on.

Table 1.10
The Changing Shape of the United States Brewing Industry (Million Barrels)

Year	*Anheuser-Busch*	*Miller*	*Coors*	*Schlitz*	*Pabst*	*Miscellaneous*
1940	2.5	0.5	0.1	1.6	1.6	Schaefer 1.4, Falstaff 0.6, Schmidt 0.6, Stroh 0.5
1950	4.9	2.1	0.7	5.1	3.8	Schaefer 2.8, Falstaff 2.3, Schmidt 1.1, Olympia 0.6, Stroh 0.5
1960	8.5	2.4	1.9	5.7	4.7	Falstaff 4.9, Carling 4.8, Schaefer 3.2, Stroh 2.1, Schmidt 1.8, Olympia 1.5, Genessee 0.8, Heileman 0.6, Pearl 0.5
1970	22.2	5.2	7.3	15.1	10.5	Schaefer 5.7, Falstaff 5.4, Carling 4.8, Olympia 3.4, Stroh 3.3, Heileman 3.0, Schmidt 3.0, Pearl 1.8, Genessee 1.5
1975	35.2	12.9	11.9	23.3	15.7	Schaefer 5.9, Olympia 5.6, Stroh 5.1, Falstaff 5.0, Heileman 4.5, Carling 4.1, Schmidt 3.3, Genessee 2.2, Pearl 1.4, Rainier 0.9, Blitz Weinhard 0.8
1980	50.2	37.3	13.8	15.0	15.1	Heileman 13.3, Stroh 6.2, Olympia 6.1, Falstaff 3.9, Schmidt 3.6, Genessee 3.6, Schaefer 3.6
1985	68.0	37.1	14.7		11.5 (S & P)[a]	Stroh 23.2, Heileman 16.5, Genessee 3.0
1990	84.6	46.2	19.2		8.2 (S & P)[a]	Stroh 16.1, Heileman 11.2, Genessee 2.2, Gambrinus 0.7, Boston 0.1
1995	84.8	47.7	18.7		?	Genessee 1.8, Gambrinus 1.5, Boston 1.0
1999	95.1	44.0	20.1		11.6[b]	Genessee 1.3, Gambrinus 3.3, Boston 1.1

Source: Courtesy of Dr. W. J. Vollmar.
Note: Value rounded up to first decimal point. Blank cells represent companies defunct as separate organizations.
[a] S & P incorporated Pabst and Falstaff.
[b] Includes Stroh volume.

Table 1.11
Top U.S. Beer Brands 1999

Brand	*Million hl*	*% share*	*% change since 1998*
Budweiser	41.9	17.5	−3.3
Bud Light	34.0	14.2	+11.1
Miller Lite	19.1	7.9	+2.2
Coors Light	18.8	7.8	+5.3
Busch	9.4	3.9	−1.5
Natural Light	9.0	3.8	+5.5
Genuine Draft	6.8	2.8	−2.1
High Life	6.4	2.7	+5.8
Busch Light	6.0	2.5	+4.6
Corona	5.7	2.4	+19.9

Source: Brauwelt International.

compared to bottles, and metal kegs, which allowed for more robust shipping of draught products—reinforced the reach of the major Brewers as they took their merchandise to the great cities across the nation. The American taste rapidly swung toward the pale, brilliantly clear, relatively dry and delicately flavored products that are now the norm and that represent two thirds of beer sales in the United States. The top four brands in the United States in 1999 were Budweiser, Bud Light, Miller Lite, and Coors Lite, with combined sales of some 114 million barrels (table 1.11). Over $500 million is spent on advertising them. These brands are also enormous sellers globally (table 1.12).

A Brief History of Brewing Science

By the end of the seventeenth century only one textbook on brewing had been produced, by Thomas Tryon in 1691: it was entitled *A New Art of Brewing Beer, Ale, and Other Sorts of Liquor so as to render them more healthful. . . . To which is added the art of making malt. . . . Recommended to All Brewers, Gentlemen and others who brew their own drink.* Many years would elapse before the science began slowly to emerge that would explain what was happening in the malting and brewing processes and how they could be modified and controlled to ensure the production of consistent products of high quality. It is this science, and the refined technology that developed from it, that forms the heart of this book.

In 1680 a 48-year-old draper from Delft in Holland, Antonie van Leeuwenhoek (fig. 1.14), reported to the Royal Society in London how he had

Table 1.12
The World's Biggest Beer Brands (2000)

Brand	*Million hl*
Budweiser and Bud Light	87.3
Asahi Super Dry	24.5
Corona	23.8
Skol	23.7
Coors	23.1
Brahma Chopp	21.0
Heineken	20.4
Miller Lite	20.0
Castle	14.6
Busch	14.5

Source: Canning and Filling, January 2002.

developed a microscope that had enabled him to inspect a drop of fermenting beer and reveal therein something we now recognize as yeast cells. One hundred fifty years later, Charles Cagnaird Latour in France and Theodor Schwann and Friedrich Kutzing in Germany independently claimed that yeast was a living organism that could bud. They were ridiculed by the German scientists Justus von Liebig (fig. 1.15) and Friedrich Wohler, who insisted (it is believed with sarcasm) that yeasts were eggs that turned into little animals when put into sugar solution. Liebig and Wohler, who clearly had little sympathy with matters biological, suggested that these animals

> have a stomach and an intestinal canal, and their urinary organs can be readily distinguished. The moment these animals are hatched they begin to devour the sugar in the solution, which can be readily seen entering their stomachs. It is then immediately digested, and the digested product can be recognized with certainty in the excreta from the alimentary canal. In a word, these infusoria eat sugar, excrete alcohol from their intestinal canals, and carbonic acid from their urinary organs. The bladder, when full, is the shape of a champagne bottle, when empty it resembles a little ball; with a little practice an air-bladder can be detected in the interior of these animalculae; this swells up to ten times its size, and is emptied by a sort of screwlike action effected by the agency of a series of ring-shaped muscles situated in its outside. [2]

It was another Frenchman who sorted the matter out. Louis Pasteur (1822–1895; fig. 1.16) became professor of chemistry at Lille University

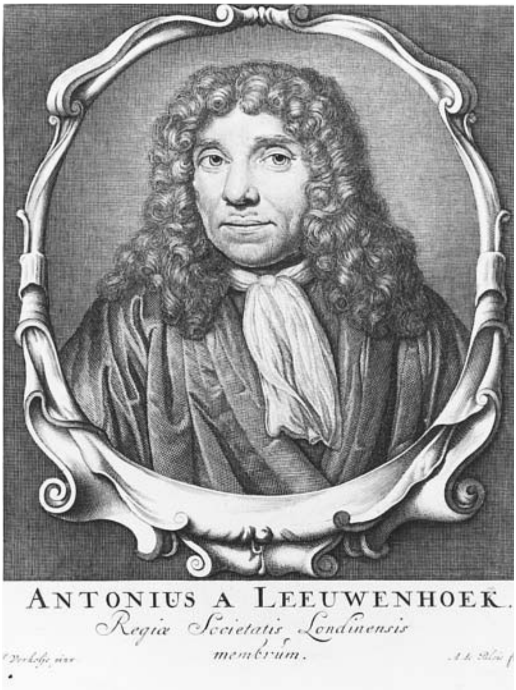


Figure 1.14 *Antonie van Leeuwenhoek. Microscopy was just a hobby for van Leeuwenhoek. He made his own microscopes out of the magnifiers used by his father-in-law, a cloth merchant. Van Leeuwenhoek studied a range of samples: red blood cells, spermatazoa, aphids—and the bacteria in scrapings from between his teeth! He didn't, of course, know what they were—he simply referred to them as "flora of the mouth."* *Reproduced courtesy of the Library and Information Center, Royal Society of Chemistry.*

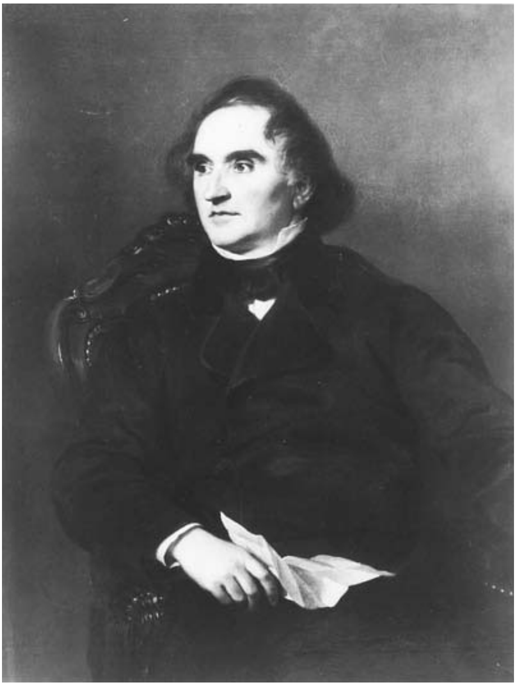


Figure 1.15 *Justus von Liebig. Born in Darmstadt, Germany, in 1803, he was only 19 when he earned his doctorate. In 1824, King Ludwig I of Bavaria provided von Liebig with a laboratory at the University of Giessen, and he taught there until 1852, when he moved to Munich. It is surely ironic that von Liebig was expressing his eccentric opinions on fermentation from one of the great homes of brewing.* *Reproduced courtesy of the Library and Information Center, Royal Society of Chemistry.*

Figure 1.16 *Louis Pasteur was only mediocre as a student of chemistry at the Sorbonne. But he developed, and in 1876 he penned a book entitled* Études sur la Biere (Studies on Beer). *Reproduced courtesy of the Library and Information Center, Royal Society of Chemistry.*

and was urged by the local Brewers to explain the difficulties they were having with beer going sour after fermentation. He demonstrated that the infection was due to airborne organisms that he could trap in gun-cotton and that they could be inactivated by heat. By 1860, this tanner's son from Dole was able to conclude that "alcoholic fermentation is an act correlated with the life and organization of the yeast cells."[3]

The brewing historian Ray Anderson has eloquently described how Pasteur's role, while pivotal in the history of brewing science, was not absolute. As Anderson says, "Pasteur's genius—and make no mistake he was a genius—was in bringing together disparate elements and making the whole greater than its parts. What sets Pasteur apart is the rigor of his scientific method, the clarity of his vision in recognizing the significance of his results and in applying his findings to practice."[4]

Anderson emphasizes the contributions of those such as Carl Balling, who spoke in the 1840s of the living nature of yeast in his lectures to brewers in Prague. James Muspratt and Heinrich Bottinger (the latter head brewer of a brewery in Burton-on-Trent) disagreed with their teacher Liebig and recognized the criticality of live yeast. Jean Chaptal, a French chemist, in 1807 associated films of vegetation on wine with souring. In fact, the present well-controlled, highly efficient, reliable, and multibillion-dollar brewing industry is testimony to the researches of diverse eminent scientists who worked not only on yeast but on the germinative properties of barley, the composition of hops, and the refinements of the malting and brewing processes in their entirety.

A seminal moment in the shaping of the modern brewing industry came in 1883. Emil Christian Hansen (fig. 1.17), head of the Physiological Department of the Carlsberg Laboratories in Copenhagen, proposed that the all-too-frequent occurrences of brews that produced unsellable product were due not necessarily to infection by bacteria as Pasteur had proposed but rather to the presence of “wild yeasts.” The term “wild yeast” persists to this day and is really a reference to any yeast strain other than the one that the Brewer intends should be used to ferment the Brewer’s beer, for it is that yeast that contributes substantially to the unique character of a beer. It was Hansen who perfected a system for purifying yeast into a single, desired strain, and this forms the basis for the brand-to-brand individuality of beers to this day.

In the ensuing century, the technology for the malting of barley and brewing of beer advanced remarkably, building on the scientific explorations

Figure 1.17 *Emil Christian Hansen (1842–1909). He was the son of a house-painter from Ribe in Southern Jutland. His father was quite a character; among his exploits were a stint in the French Foreign Legion. Young Emil Christian was struck by his father’s words: “a person can do everything as long as he has the will to do it.” Academically, the boy developed slowly, becoming a house-painter himself while also painting pictures (he was rejected by the Danish Royal Academy of Arts) and writing stories. His attention then turned to science, and he became something of an authority on peat bogs, before turning his attention to the physiology of yeast under Professor Pete Panum in Copenhagen in 1877. It was at this time that he joined Carlsberg. Reproduced courtesy of Carlsberg, from* The Carlsberg Laboratory 1876–1976.

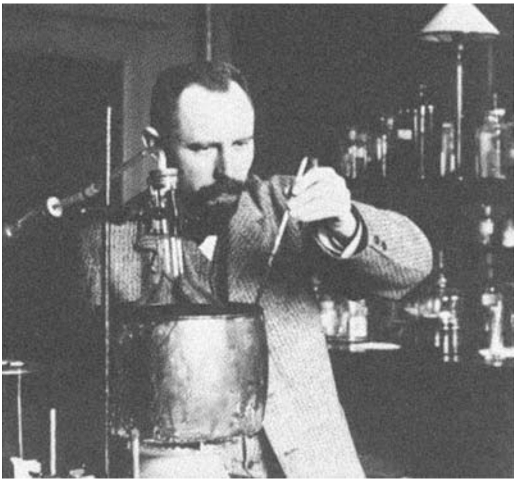


Figure 1.18 *Soren Sorensen (1868–1939). A farmer's son from Slagelse in Denmark, Sorensen began to study medicine but soon shifted to chemistry. He became head of the Chemical Department of the Carlsberg Laboratory in 1901.* *Reproduced courtesy of Carlsberg, from* The Carlsberg Laboratory 1876–1976.

of many gifted scientists worldwide. The processes are enormously more efficient now than they were even 50 years ago. For instance, the malting process is now completed in less than a week, whereas it took twice as long half a century ago. Brewing can take as little as one to two weeks, although many Brewers insist on longer processing times: Brewers take pride in their products and, while striving for efficiency, won't take short cuts if quality would be jeopardized.

Brewing scientists, too, have bequeathed to society many concepts that are now accepted as commonplace. For instance, James Prescott Joule was employed in a laboratory at his family brewery in Salford, England, when he contemplated the research that led to the first law of thermodynamics. Soren Sorensen (fig. 1.18), working in the Carlsberg Laboratories, explained the concept of pH (the universal scale for measuring acidity and alkalinity) and its importance in determining the behavior of living systems, notably through an impact on enzymic activity. W. S. Gosset, who was breeding new varieties of barley and hops for Guinness, published under the pseudonym "Student," a name familiar to those statisticians everywhere who apply the T-test. And not least, of course, the impact of Pasteur on modern society extends far beyond beer.

This chapter has described the magnitude of the world beer market, the pressures that come to bear on it and that influence production outputs, and how its shape today is a direct reflection of a longstanding pedigree. It's now time to explain the essence of the remarkable processes involved in converting barley and hops into the world's favorite alcoholic drink.

2

Grain to Glass

The Basics of Malting and Brewing

This chapter presents an overview of the entire brewing process, from barley to beer. In subsequent chapters the individual stages are covered in more detail.

The staple ingredients from which most beers are brewed are malted barley, water, hops, and yeast. The nature of beer is derived from these raw materials and the two separate (but related) processes that have been used to make this drink for thousands of years. In Germany, legislation decrees that beer production must involve these materials *alone*. Excellent beers are produced in Germany, but so, too, are they produced in the rest of the world, where there is greater flexibility in the materials available to the Brewer. The wherewithal to use a selection of adjuncts, for instance, enables the Brewer to provide the consumer with an excellent selection of beers to meet every drinking occasion. The opportunity, too, to use process aids such as clarifying agents and stabilizers ensures the Brewer's capability to produce, in an economic manner, beer that will have good shelf-life—benefits that are passed on to the consumer. The Brewer is not unrestricted: in all countries legislation dictates what may be legitimately employed in making beer, what the label has to declare, and how beer may be advertised. In some countries, such as the United Kingdom, the package must give a date before which the beer should be consumed. At present, though, U.K. Brewers do not have to provide ingredients labeling on the container, whereas in some countries they do. In the United States, the Food and Drug Administration (FDA) and

Figure 2.1 *Barley. The grain develops on the ear. Each grain is generally referred to as a "corn." The "whiskers" or "beards" (awns) are distinctive of barley. Courtesy of Michael Lewis.*

the Bureau of Alcohol, Tobacco, and Firearms (BATF), which is within the Treasury Department, regulate all aspects of the wholesomeness of beers.

At the simplest level, malting and brewing represent the conversion of the starch of barley into alcohol. Brewers are interested in achieving this with maximum efficiency, in terms of highest possible alcohol yield per unit of starch. At the same time, though, they insist on consistency in all other attributes of their product—foam, clarity, color, and, of course, flavor.

When we speak of barley in a brewing context, we are primarily concerned with its grain, the seeds growing on the ear in the field: it is these that are used to make beer (fig. 2.1). Barley grains are hard and difficult to mill. Try chewing them if you will—but have a good dentist on hand! They also don't taste particularly pleasant, drying the mouth and leaving a harsh, astringent, and extremely grainy aftertaste. Indeed, beer brewed from raw barley is not only troublesome in processing but also has a definite grainy character. It must have been pure serendipity when the process of malting was discovered some 100 centuries ago, but out of such happenstance has sprung up a mighty industry responsible for converting this rather unpleasant cereal into a generally satisfying malt.

Malting

A simple diagrammatic representation of the malting process is shown in figure 2.2. Barley (fig. 2.3) is first steeped in water, which enters the grain through the micropyle and distributes through the food reserve (the starchy endosperm). The water first enters the embryo, which springs into life. The embryo is the infant plant and produces hormones that journey to the tissue (called the aleurone) that immediately surrounds the starchy endosperm. These hormones switch on the production of enzymes, and these first chew up the walls of the cells in the aleurone and then move into the starchy endosperm, digesting its walls and some of its protein (fig. 2.4). As these are the materials that make barley hard, it is this hydrolysis that renders the grain friable, easily chewed, and subsequently more readily millable in the brewery. The experienced maltster will evaluate how well this "modification" process is proceeding by rubbing or squeezing individual grains between her fingers. Happily, in the relatively short periods of time needed to soften grain (typically four to six days), only 5–10% of the starch in the endosperm is removed, although the starch-degrading enzymes produced in the aleurone do bore holes in it. The starch is the material the Brewer subsequently uses as a source of fermentable sugars to make beer: the more that survives malting, the better!

The cell wall and protein polymers are degraded into small soluble molecules, which migrate to the embryo for its nourishment. Using this food, the embryo starts to germinate and produce rootlets and a shoot (acrospire). Excessive production of these tissues is not desirable, as this consumes material that can otherwise to be sold to the Brewer. The rootlets emerge through the micropyle and become the first obvious manifestation of ger-

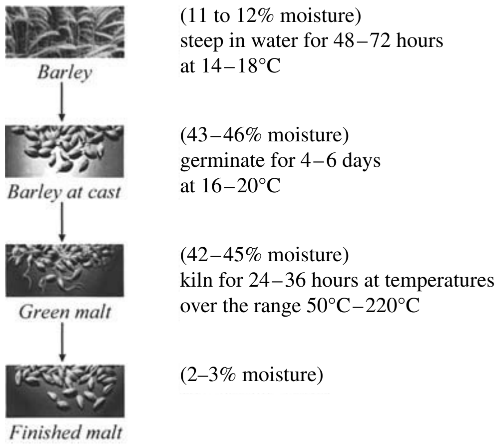


Figure 2.2 *The malting process.*

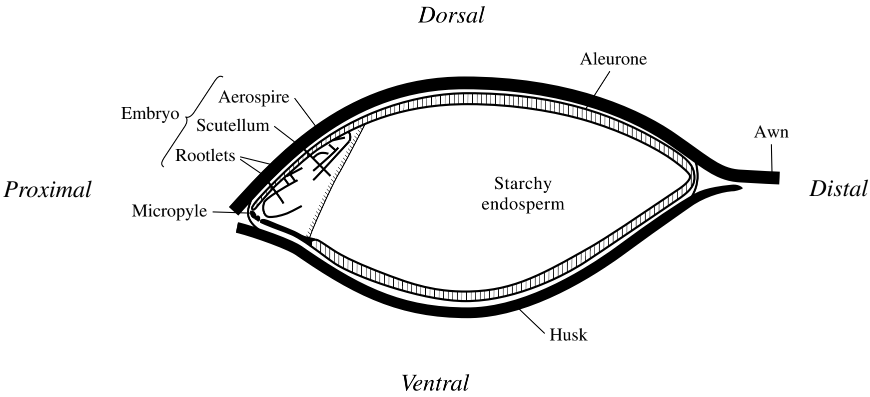


Figure 2.3 *The basic structure of the barley kernel.*

mination. The acrospire, of course, heads in the opposite direction of the roots (as shoots tend to do!) and grows beneath the husk, eventually to appear out of the distal tip. If the acrospire does appear in a commercial maltings operation, then germination has gone too far.

When the germination stage is deemed to have proceeded for a long enough period, it is stopped by heating the grain in a process referred to as kilning. The aim is to drive off water until the moisture level in grain is below 5%, when the metabolism of the barley will be halted and the product stabilized. The heating process needs to be conducted carefully. If the brewer is to get access to the starch in the grain, he will need to use the enzymes (the amylases) that are present in the grain and that are mostly produced during germination. Enzymes are, for the most part, susceptible to death by heat, and they are particularly sensitive at higher moisture levels. For this reason, the kilning process is started at quite a low temperature (perhaps 50°C). When about half of the water has been removed, the temperature can be raised, and this ramping will continue according to a preset regime, depending on the nature of the malt required.

Malts destined to go into the production of ales are kilned to a higher temperature. This has two implications: the first is that these malts will be darker. In the kilning process, the breakdown products (amino acids and sugars) released from proteins and carbohydrates during germination combine together to form what are called melanoidins, which are colored. The higher the temperature (and the more breakdown products in the first place—i.e., the more extensively modified is the grain), the darker the color.

The second implication of higher kilning temperatures is the development of complex flavors. The pleasant flavors that we associate with malt and that enter, for instance, into malty bedtime drinks, are produced during the kilning process, as well as from the interactions among the breakdown

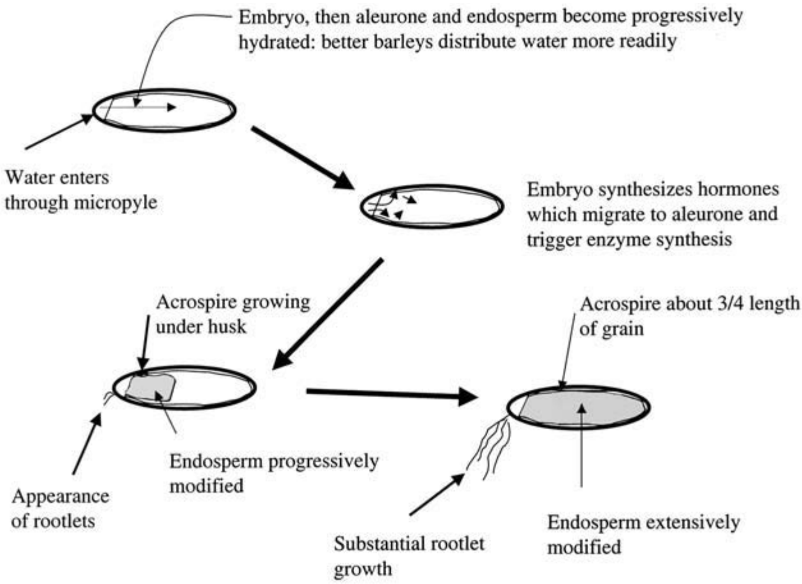


Figure 2.4 *A schematic depiction of the events during barley steeping and germination.*

products of protein and carbohydrate. If malt is kilned to particularly high temperatures, it is possible to make especially dark products (the sort that are used to color stouts) and to develop flavors described as "burnt" and "smoky."

Malts destined for lager-style beers are generally less extensively modified than those aimed at ale production (i.e., they contain less amino acid and sugar), and they are kilned to a relatively mild regime. They therefore develop less color and give quite pale or straw- or amber-colored beers. They may also deliver a wholly different kind of flavor into beer, one that tends to be more sulfury.

Brewing

It is very unusual for a maltings and a brewery to be on the same site, even for so-called brewer-maltsters, which are Brewers that produce their own malt.

The first step in brewing (fig. 2.5) is the milling of the malt. The phrase "grist to the mill" is, of course, an accepted part of the English language. Malt is the principal grist material used for brewing, but there may be others, too, such as roasted malt or barley, corn, and rice.

All of the unit operations within the brewery must be performed correctly if the process is to be efficient and trouble free. Milling is as important

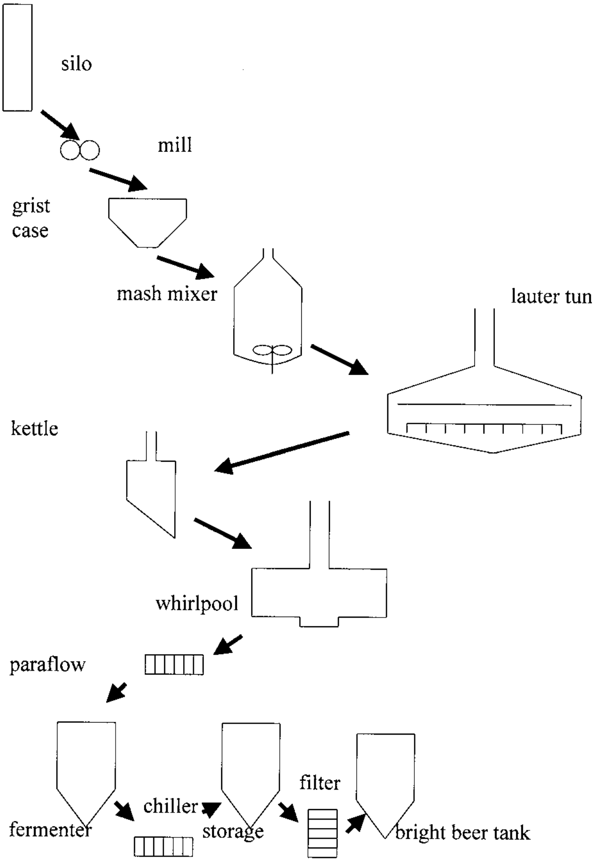


Figure 2.5 *The brewing process.*

as any stage that follows in the brewery. The aim in milling is to produce a distribution of particles that is best suited to the subsequent processes in the brewhouse. In large part the malt should be converted to a flour, with particles small enough to enable access of water. This will hydrate the particles and enable the enzymes in the malt to be activated. It will also "solvate" the substrate molecules (principally starch) that the enzymes are targeting. For most brewhouses, though, it is important that the husk component of the malt remains as intact as possible after milling. This is because it will be used to form the filter bed through which the solution of sugars produced in the mashing operation will be recovered in as "bright" a condition as possible.

The milled grist is stored briefly in the grist case, before going to the mash mixer (mash tun, conversion vessel). Here it is mixed intimately with warm water to commence the hydrolysis process. Mashing is often commenced at a relatively low temperature (say 45–50°C) to enable the more heat-sensitive enzymes to do their job. These include the enzymes that degrade any cell-wall polysaccharides that survived the malting process. Then, after perhaps 20 minutes, the temperature is raised to at least 65°C, for it is at this temperature that the starch is gelatinized. This process can be likened to melting. It involves the conversion of starch from a crystalline, difficult-to-digest structure to a disorganized state readily accessed by the amylase enzymes responsible for chopping it up into fermentable sugars. Happily, the amylases largely survive this higher temperature. The mash is held for a period of perhaps an hour, before the temperature is raised once again, this time typically to 76°C. This serves to stop most enzymatic activity, as well as reducing viscosity and sticking particles together, thereby improving the fluidity of the mash.

In most breweries the sugar solution produced (wort; rhymes with "Bert") is separated from the spent grains in a vessel called a lauter tun. The bed depth is relatively shallow, and rakes are used to loosen the bed structure and overcome compacting. Efficient lautering is a skilled operation, the aim being the recovery of as clear a wort as possible ("bright wort") containing as much as possible of the soluble products of mashing (the sum total of which is called "extract"). It is also generally important that the recovered wort is relatively concentrated—so-called high-gravity wort—if production throughput in the subsequent fermentation stage is to be maximized. To facilitate washing of the breakdown products (made from carbohydrate and protein) out of the mash bed, hot water is used to "sparge" the grains. Clearly too much water must not be used if the wort is not to be excessively diluted. The aim, though, is extraction of as much of the fermentable material as possible from the grains within the restricted time available—the more rapidly the wort can be recovered from the residual grains, the more brews can be performed per day. Almost without exception, the spent grains are sold off as cattle food.

Wort flows directly (usually) from the lauter tun (or one of the other wort separation processes, which I will discuss in chapter 6) to the kettle (sometimes called the "copper," despite the fact that these days they are mostly fabricated from stainless steel).

Wort boiling, which is performed in this vessel, serves several functions. Foremost among these is the extraction of bittering materials and of aroma components from hops. Traditionally hopping was done by adding whole cone hops, and this is still practiced in a good many breweries. The hop residue still remains after the boil and, as in the situation with malt husk and wort separation, the residual hops are used in a so-called hop back to form the filter medium through which the bittered wort is separated. More frequently these days, hops will have been preprocessed. It is very common for hops to be milled and pelletized before entering the brewery, in which case vegetative matter does not survive intact, and the postkettle vessel is the whirlpool (see hereafter). Alternatively, liquid extracts of hops are used.

Hops contain resins that are extracted in the wort boil and converted into more soluble and bitter forms. Hops also possess a complex mixture of essential oils, and it is these that provide the different hoppy characters that can be associated with beers. These molecules are quite volatile and will evaporate to a greater or lesser extent in the boil. Hops added at the start of a boil, which typically lasts for one hour, will lose essentially all of their oils. For this reason, in traditional lager brewing in Europe, a proportion of the hops is held back for addition during the final few minutes of the boil, thereby enabling a proportion of the essential oils to survive and provide distinctive aroma notes. This procedure is called "late hopping." In traditional ale brewing in the United Kingdom, a handful of hops is added to the cask prior to its leaving the brewery. This so-called dry hopping makes for a much more complex hop character in a beer, as there is no opportunity for evaporation of any of the oils.

Apart from the extraction of substances from hops, wort boiling serves to concentrate wort to a greater or lesser degree (depending on the rate of evaporation allowed, which can range from 4 to 12%), driving off unwanted flavor molecules, inactivating any enzymes that might have survived mashing and wort separation, and sterilizing the wort. (Because of boiling, and because the antimicrobial bitter compounds are introduced during it, there was a time when beer was far safer to drink than the local water, which carried diseases such as cholera and typhoid. It may still be the case in some countries that beer should be your preferred drink, for this reason.) Most important, the boiling also causes coagulation of much of the protein from the malt, a process that is promoted by tannin materials extracted from the malt and hops. This precipitation, to form an insoluble complex called trub (rhymes with "pub" in England but with "lube" in the States!), is important, as these proteins, if not removed here, will be capable of dropping from solution in the subsequent beer to form unsightly hazes and sediments.

In most breweries the next stage involves the whirlpool, first used by the Molson company in Canada. The principle was discovered by Albert Einstein, stirring his cuppa in pre–tea bag days. He noticed that the leaves in the swirling liquid collected at the center of the cup. Eureka! In a brewery, the boiling wort is passed tangentially into a large vessel (the whirlpool, sometimes called a hot wort receiving vessel) and allowed to swirl there for an hour or so. Centripetal forces make the trub collect in the central cone at the base of the whirlpool, leaving a bright wort above it. The removed trub is often mixed in with the spent grains (and mixed well, because of its intense bitterness!) before being sold for cattle food.

The wort is now almost ready for fermentation—but it must be cooled before yeast is added. This is achieved using a heat exchanger, commonly referred to as a “paraflow,” in which the wort is flowed through channels against a flow of cold water or other coolant in adjacent channels. Heat transfers from the wort to the water, the latter now being recovered for cleaning duties. The wort will have been cooled to the desired temperature for fermentation, which may be as low as 6°C for traditional lager brewing in mainland Europe and as high as 15–20°C for ale brewing in England.

Prior to the addition of yeast, a little oxygen (or air) will be bubbled into the wort. Although the fermentation process leading to the production of alcohol is anaerobic, yeast does require some oxygen, which helps it to make certain parts of its cell membrane and allows it to grow.

The traditional distinction between brewing yeasts divides them into two types: top-fermenting yeast and bottom-fermenting yeast. The first type was traditionally used for ale brewing in open fermenters in the United Kingdom, and such strains have their name because they migrate to the surface of the beer during fermentation. Bottom fermenters, as the name suggests, settle to the base of the fermentation vessel, and they are traditionally associated with the production of lager-style beers. These days the distinction is blurred, insofar as ales and lagers are frequently fermented in the same type of vessel. Although traditional fermenting systems survive, the most common system is the cylindro-conical tank, within which the distinction between different flotation characteristics of yeasts becomes blurred.

Fermentation is primarily concerned with the conversion of sugars into alcohol, and the rate at which this occurs is basically in direct proportion to the temperature and to how much yeast is “pitched” into the fermenter. Ale fermentations can be as fast as two or three days, whereas traditional lager fermentations can take more than a fortnight to be completed. The process, however, represents more than simply an alcohol production factory; otherwise the temperature employed would be substantially greater. Brewery fermentation is also about producing a subtle mix of flavor compounds. The balance of these will depend on the yeast strain involved, which is why Brewers jealously guard and protect their own strains: the character of a beer often depends as much as anything else on the yeast, particularly for the more subtly flavored lagers.

All shades of opinion govern what happens next. The traditional Brewer of lager beers will insist that a beer must be stored (lagered) on a decreasing temperature regime from 5°C to 0°C over a period of months. Others are convinced, however, that no useful changes in beer quality occur in this time and that this period can be substantially curtailed. All are agreed, however, about the merits of chilling beer to introduce stability to it. For most

Brewers this involves taking the beer to as low a temperature as possible, short of freezing it. In practice this means −1°C for a few (perhaps three) days. Whereas heat-precipitable proteins are removed in the boiling and whirlpool operations, it is the cold-sensitive proteins that drop out at this conditioning stage. The colder the better: −1°C for three days is far better than 1°C for two weeks. Of course, not all beer is chilled: the traditional English ale, for instance, is clarified using protein preparations known as isinglass finings, which are extracted from the swim bladders of certain types of fish. The isinglass promotes the settling of solid materials from beer.

Once again, the beer needs to be clarified. This can be achieved using various types of filter. Generally clarification will be assisted by the use of a so-called filter aid, such as kieselguhr, which serves to keep an open bed through which beer can flow but also to provide pores that will trap solids. Kieselguhr is a diatomaceous earth—a mined substance consisting of the skeletons of primitive organisms.

At this stage, too, various materials may be added to promote the stability of the beer. Some of these materials remove the protein or polyphenols that cause hazes. Others are antioxidants that prevent beer from staling. Some Brewers will employ an agent such as propylene glycol alginate, derived from seaweed, to promote foam stability, though there is a strong additive-free policy for most beers in North America.

The beer is filtered into the so-called bright beer tanks, where it awaits packaging. The Brewer will ensure that it has the correct carbon dioxide (CO_2) content; CO_2 is, of course, a natural product of fermentation, but its level in bright beer may have to be increased to meet the specification. Or it may have to be lowered: some beers should contain less carbon dioxide than that which develops in deep fermenting vessels. Nitrogen gas is introduced into some beers at this stage to enhance foam stability.

Finally the beer is packaged, either into can, bottle (glass or plastic), keg, cask, or bulk tank. The packaging process must be efficient, in terms not only of speed but also quality: there should be no oxygen pickup in the beer, for this will cause the product to go stale. Consistent fill heights must be achieved to satisfy weights and measures legislation, no foreign bodies must enter the package, and, last but not least, the container must be attractive and not damaged during the filling process, which, in the case of cans, might be at a rate of over 2,000 cans per minute.

Beer Styles

Fundamentally beers may be divided into ales, lagers, and stouts. Traditionally, ales and stouts were brewed with top-fermenting yeasts, those that migrate to the surface of the fermenting vessel, in open vessels from which the yeast was "skimmed" as a means of collection. They were dispensed at relatively warm temperatures (10–20°C). Lagers, on the other hand, were traditionally produced using bottom-fermenting yeasts, which sedimented during the process and were collected from the base of the vessel; the dispensing temperature was cool (0–10°C).

In the late twentieth century, however, there was considerable blurring of the boundaries dividing these beer styles. The successful brewing companies are characterized by strong new product development programs, from which have emerged some remarkable beers that don't fall easily into any recognized classification. Where, for instance, would you pigeonhole a stout containing oysters or chocolate, ales tasting of heather, or lagers with just a hint of citrus or a whole chili? Even more fundamentally, beers that fall into an obvious genre in one market may be slotted into an entirely different category elsewhere: for instance, a beer that may be described as a "bitter" in Australia would to an Englishman be perceived as having the characteristics of a "lager."

Table 2.1 gives a breakdown of the principal beer types. "Beer snobs" will doubtless decry the absence here of names like cream ale (an ale/lager blend), scotch ale, and Dortmund. They may question the absence of concepts such as steam beer, the origins of which can be traced to the California gold rush and a demand for refreshing light drinks despite the lack of ice for lagering. Lager strains were used at warm fermentation temperatures in shallow vessels, into which the "steaming" wort was introduced to cool. Nonetheless, I believe that the entire breadth of basic styles is captured in table 2.1. It is a fact, sad or otherwise, depending on your point of view, that it is becoming increasingly difficult to classify beers. This situation has been exacerbated by the tremendous surge of new product development ideas that has characterized the brewing industry in recent years. The British market has seen (and rejected) black lagers. A similar fate befell a colorless lager in the United States. In both instances perhaps the problem was a discontinuity for the drinker between what the appearance of a beer told them and what the label said. A black lager? A beer that looks like water (apart from the head)?

Most new products have adhered to established convention in terms of appearance. Modern technology, though, has permitted the extension of the list of beer categories to light beer, ice beer, dry beer, and non- or low-alcohol beer—and the opportunities don't end there. A beer is increasingly characterized by either a technological story told about it (e.g., ice beer), an image (e.g., dry beer), or a particular property which the consumer expects from it (e.g., light beer or low-alcohol beer). It is a fact that many beers in the world are referred to as "Pilsners" or "Pils," despite falling beyond the

Table 2.1
Types of Beer

	Origin	*Typical range of alcoholic strength (% by vol.)*	*Characteristics*
Ales and stouts			
Bitter (pale) ale	Britain	3–7.5	Dry hop, bitter, estery, malty, low carbonation, copper color
Alt (i.e., "old")	Germany	4+	Some esters, bitter, copper color
Mild (brown) ale	Britain	<3.5	Dark brown, sweet, mellow
Stout	Ireland	4–7+	Roast, bitter, black
Porter	Britain	4.5–6.5	Similar to stout but less roast character
Sweet stout	Britain	3.5–4	Sweet, dark brown/black
Barley wine	Britain	8–10	Estery, copper/brown
Kölsch	Köln (Cologne), Germany	4.4–5	Pale gold, light, and dry (ale/lager hybrid)
Lagers			
Pilsner/Pils	Czech Republic	5–5.5	Late hop, full-bodied, malty, pale amber/gold
Bock	Germany	6–8%	Sulfur, malty, colors ranging from straw (Pale Bock) to dark brown (Doppelbock)
Helles	Germany	4.5–5.5	Pale amber/gold, very malty, low bitter/hop character
Märzen (meaning "March," when traditionally brewed)	Germany	4.5–6.5	Medium bitter/hop; toasted character; amber through reddish brown, the Vienna style is very similar
Dunkel	Germany	4.5–5	Copper-brown, malt/toast
Schwarzbier	Germany	3.8–5	Toast, caramel, dry, black
Malt liquor	United States	6.25–7.5	Malt/sweet, little hop, alcoholic, pale (*Many states decree that any beer containing more than 5.5% ABV must be so declared.*)
Others			
Weizenbier (wheat beer)	Germany	5–6	Cloves, slightly cloudy, straw color
Lambic	Belgium	5–7	Amber, often cloudy, fruity, sour
Rauchbier	Germany	4.3–4.8	Smoked malt, amber/brown

definition given in table 2.1. A beer nowadays seems to be what you choose to call it. For most of us, nonetheless, that still breaks down to ales, lagers, and stouts.

Ice Beers

The ice beer story is a fascinating example of how an entirely new beer concept emerged from a technology that failed at the purpose for which it was originally installed. In the 1980s, many Brewers had decided that, rather than ship finished beer around the countryside to its destination, it would make economic sense to transport the beer in a concentrated form and then reconstitute it at the point of sale. They experimented with a technique called freeze concentration, which took advantage of the fact that, if you freeze beer, the first thing to come out of solution is almost pure water, that is, ice. Most of the beer components remain in solution in a concentrated form.

Labatt, a major Canadian Brewer, was one company that experimented with the technique. They quickly realized that it wasn't going to be a winner for the purpose for which it was intended. Fortunately for Graham Stewart, their technical director at the time, and his colleagues, they hit on an even more exciting use for freeze concentration. They were looking for a new angle on beer marketing and identified *ice* as being a powerful concept that associated extremely well with beer in the perception of Canadian drinkers. It didn't take long for the intellectual leap to be made: "hey, let's chill out our beer and position a new beer genre as "ice beer." As Professor Stewart says, "after all, Canadians already knew all about putting beer out onto the window ledge in the winter, freezing ice out from it, thereby increasing the alcohol content!"

By the early 1990s a new and exciting beer story was being told, and most major Brewers had developed their own ice brands. In 1996 some 24 million barrels of ice beer were brewed in the United States, with the market share for such beers increasing by almost 4% beyond that of the previous year.

Dry Beers

The mid-1980s saw the emergence of dry beer, and through it the astonishing growth of the Japanese Brewer Asahi. It launched a new brand called Super Dry and saw a 25% increase in its market share within three years. As the name suggests, it is a straightforward concept equivalent to that with dry wine: a lager with a relatively low proportion of residual sugar. But clever marketing, and the characteristic outstanding package quality associated with Japanese Brewers, made it a clear winner. It was a product deliberately designed to appeal to as many people as possible through having no extreme flavor characteristics that might alienate sections of the populace. In no time it was followed by other dry beers ("me too's"), and a dozen countries contributed over 30 new brands of dry beer.

Light Beers

Premium light beers now constitute the most popular beer category in the United States and have come a long way from the first reduced-calorie brew made by Rheingold, called Gablinger's. These beer styles are differentiated by their content of residual carbohydrate: standard premium beers contain a proportion of carbohydrate, which survives the fermentation process, whereas a light beer has most or all of this sugar removed (by techniques I will discuss in chapter 7). Therefore, these beers have fewer calories, provided they don't contain extra alcohol, which in itself is a contributor to calorie intake. Thus it is perhaps no surprise that, in a market (U.S.) where 24% of all beer is consumed by women, the proportion of light beers drunk by women has increased to 30%.

Draft Beers

The word "draft" ("draught" in the British Isles) can refer to two entirely distinct beer types. Traditionally it refers to beer that is dispensed from kegs or casks via pipes and pumps, or indeed straight from the cask, as is still the case for some of the traditional English ales. The term is also used, however, to describe small pack beer that has not been pasteurized but rather sterile-filtered. The marketers had a new angle for canned beer: "as nature intended." Much beer worldwide is now marketed using this angle of it being "non–heat treated." For instance, no beer in Japan is pasteurized. The fact is, however, that, provided the oxygen levels in the beer are low beforehand, pasteurization has no adverse impact on flavor and is actually to the benefit of foam, which can deteriorate with time in nonpasteurized beers. It certainly is a curiosity that the lack of pasteurization is taken by some as a positive thing. I can't imagine customers caring much for this if we were talking milk!

From Cask-Conditioned to Nitrogenated Beers

The big growth market for beers in the United Kingdom is in nitrogenated products. Their emergence is an informative lesson in how modern technology can throw up products whose origins are in traditional practice.

The classic beer style in England is nonpasteurized ale with relatively low carbon dioxide content. Happily, many famous brews of this type continue to be produced. The production of traditional English ales involves them going from fermentation into casks, to which are added hops, sugar, and finings materials that help the residual yeast to settle out. That yeast uses the sugar to carry out a secondary fermentation, which carbonates the beer to a modest extent. The product is not pasteurized and must be consumed within a few weeks. It is characterized by a robust hoppy flavor but also by much less gas "fizz" than other types.

Again, in the mid-1980s and with the projected demographic shift to more drinking at home, as opposed to pubs and bars, marketers in the United Kingdom decided that they would really like to be able to sell this type of beer in cans for domestic consumption. The problem was the low CO_2 content; that gas is generally required to pressurize and provide rigidity to cans, as well as to put a head on beer. For cask beers, the handpump, characteristic of the English pub, does the work in frothing the beer. For "normal" canned beers, the relatively high gas content does the job for you when you pour it. So how could the foaming problem be overcome for canned beers containing relatively little carbon dioxide? The answer was the "widget," a piece of plastic put into the can that flexes when the can is opened and causes bubbles to come out of solution (see chapter 3). This technology was invented by Guinness, a Brewer with a long tradition of producing stouts with superbly stable heads. Allied to this was the realization that nitrogen gas makes vastly more stable foams than does carbon dioxide, again a technology that had been pioneered by the Irish company and taken advantage of by many Brewers to enhance the heads on their draft beers. So nitrogen was included in the cans—dropped in at canning in its liquid form. Not only does the nitrogen help the foam but it also smoothes out the palate, enhancing the drinkability of some of the beers that contain it, notably the stouts. The sales of canned beer with widgets zoomed, and, seeing this, Brewers recognized the potential for so-called nitrokeg beers, where the beer is on draught dispense but is characterized by low CO_2 and the presence of N_2. The merits of nitrogen and widgets were not appreciated by every Brewer. Tired of complaints about the canned beer having taken a turn for the worse since the introduction of the "lump of plastic," one English company reversed matters, eliminated the device, and proudly announced on the label "widget-free ale." Applause from this author, for one.

Non- and Low-Alcohol Beers

"Normal" beers range in their alcohol content from 2.5 to 13%. To a Bavarian used to her beers possessing 6% alcohol or more, the regular tipple of the English ale drinker at, say, 4% might be viewed as "low alcohol." Non- and low-alcohol beers (NAB/LABs) can be classified in many ways. I will define them here as beers containing less than 0.05% or less than 2% alcohol (by volume), respectively.

While there are a few successful NAB/LABs in the world, they are the exception rather than the rule. For many people it is a contradiction in terms to associate a beer with low alcohol: after all, what is a beer if it doesn't deliver a "kick"? The rationale behind developing such beers in the first place is an interesting one; it is largely based on the proposal that peer pressure among drinkers convinces some people of the need to be seen to be drinking a product that is indistinguishable (by sight) from a normal beer but has less alcohol, thereby enabling them to drive. Increasingly, it has been appreciated that this peer pressure phenomenon was overstated and that educated consumers will happily drink an established nonalcoholic product, say a juice or a cola, if the circumstances demand it. It seems that the only justification for purchasing a beer of low alcohol content is if it is pleasing to the palate, and that certainly hasn't always been the case for many such beers. The shortage of quality products in this genre is reflected in the statistics: in the United Kingdom NAB/LABs grew to occupy 1.1% of beer sales in 1989, but this had declined to 0.3% of sales just six years later.

This type of product has been made in many ways, and I will mention some of them later. Perhaps the most common techniques are to limit alcohol formation in fermentation or to strip out the alcohol from a "normal" beer. In the first case the yeast can be removed from the fermenting mixture early on, or indeed the wort that the yeast is furnished with may be produced in such a way that its sugars are much less fermentable. Alcohol can be removed by reverse osmosis or by evaporation using vacuum distillation. It should come as no surprise that attempts to remove alcohol will also result in the stripping away of desirable flavors. Equally, if a fermentation is not allowed to proceed to completion, these very flavor compounds are not properly developed, and undesirable components derived from malt are not removed. Either way, the flavor will be a problem. And if one considers that ethanol itself influences the flavor delivery of other components of beer, as well as itself contributing to flavor, then it is apparent why good NAB/LABs are few and far between.

Chapter 4 and later chapters describe in greater depth the various stages involved in going from barley to beer. First, though, in the next chapter I will further explore the aesthetic attributes of product that the Brewer is painstakingly brewing and the quality parameters that make beer such a refreshing and wholesome drink.

3

Eyes, Nose, and Throat

The Quality of Beer

The consumer of beer drinks as much with the eyes as with the mouth. Certainly beer drinking can be as visually pleasing as it is thirst quenching. The quality attributes of beer that are perceived by the eye can certainly influence our perception of flavor, as demonstrated by a simple experiment. Try adding a few drops of a flavorless dye (the type you may use in your kitchen) to a lager such that the color darkens to that more typical of ale. People presented with this beer will judge its flavor to be closer to that of an ale than a lager, whereas if they are blindfolded they certainly won't be able to tell apart the taste of the beer before and after the dye has been added.

Color is just one visual quality parameter of beer. Most people (other than those smitten with hefeweissens) prefer their beers to be sparkling bright, with no suggestion of cloud or haze. However, there is variation in the extent to which drinkers like a head of foam on beer. In some countries a copious delivery of foam on dispense is essential: for instance, it is traditional in countries such as Belgium for as much as half the contents of the glass to consist of froth. In the United Kingdom, there are distinct regional differences: in some places, for example London and the Southeast, foam seems frequently to be regarded as an inconvenience. By contrast, a stable head, perhaps 2 inches deep, is generally required in the north of England. But unlike, say, the Belgian, many an Englishman appears to want foam *and* a full measure of beer. Matters reached a head (one might say) when the status of beer foam was challenged in the courts of law. Those insisting on a full pint of liquid challenged landlords who dutifully dispensed the beer with a head. The most recent High Court judgment was that a reasonably sized head *should* be regarded as an integral feature of the beer, but that the customer is within his rights to insist on a full measure of liquid beer. Such concerns are only relevant, of course, for draft beer. For beer in cans and bottles, the volume is fixed. Whether a head is generated or not is more often in the hands of the customer than the bartender. Indeed, that's if the beer gets poured at all. Some prefer their beer directly out of the bottle or can, in which case foam (and color and clarity, for that matter) assume a more academic dimension.

In just the same way that color influences the perception of the flavor of a beer, so too does the head seem to affect a drinker's judgment (fig. 3.1). Again there is undoubtedly a psychological component at work here. It is, however, likely that the presence of a foam does have a direct bearing on the release of flavor components from the beer: in other words, a beer will smell differently when it does as opposed to when it does not display a head of foam. Not only that, but there are substances present in beer that have a tendency to move into surfaces such as the bubble walls in foam and are therefore called "surface-active compounds." These include the bitter compounds, and so the foam has proportionately more bitterness than has the rest of the beer.

You can see, then, that long before a drinker raises the glass to her lips, she will have already made some telling judgments on its quality, drawn from visual stimuli alone: the quality of the can or bottle, the "font," if the beer is on draft dispense, the appearance of the foam, the color, and whether the beer is cloudy. And all this is quite apart from the effect of other stimuli associated with the place in which the beer is being drunk: the lighting, the background music, the attractiveness of the bar layout, the foodstuffs being consumed alongside the beer, and even the company being kept. Beer flavor is important, of course, but even the most delicious of beers won't be enjoyed if all the other elements of the drinking experience are flat.

Foam

Typically a packaged beer contains between 2.2 and 2.8 volumes of carbon dioxide (that is, for every milliliter of beer there are between 2.2 and 2.8 ml of CO_2 dissolved in it). At atmospheric pressure and 0°C, a beer will dissolve no more than its own volume of CO_2. Introduction of these high levels of CO_2 demands the pressurizing of beer. Yet if you take the cap off a bottle of beer, the gas normally stays in solution. The beer is said to be supersaturated. To produce foam you must do some work.

Figure 3.1 *Foam*
Important parameters are the amount of foam produced when the beer is dispensed (foamability), the tendency for the foam to linger as the beer is consumed (head retention), and the extent to which the foam adheres to the side of the glass (cling or lacing). *Courtesy of Curt Traina.*

Foaming is dependent on the phenomenon of nucleation, that is, the creation of bubbles. Bubble growth and release occurs at nucleation sites, which might include cracks in the surface of a glass, insoluble particles in beer, or gas pockets introduced during dispense. Pockets of gas are introduced whenever beer is agitated, as anyone will tell you who has tried to open a can of lager that has been dropped.

The physics of bubble formation is far from completely understood and is astonishingly complicated. Brewers have approached the problem as much empirically as on a firm scientific foundation. For instance, glasses have been scratched to ensure a plentiful and continuous release of gas bubbles to replenish the foam, a phenomenon sometimes referred to as "beading." Draft dispense is typically through a tap designed to promote gas release. Most recently, the widget, mentioned in chapter 2 (fig. 3.2), has now even found its way into bottles.

Although beers are generally supersaturated with CO_2, foam generation is still easier and more extensive the more highly carbonated is the beer. Bubble formation is easier in liquids of lower surface tension (see "The Physics of Foaming and Flow").

Various materials can lower surface tension, among them the alcohol in beer (ethanol). Ethanol is curious, insofar as it promotes head formation at

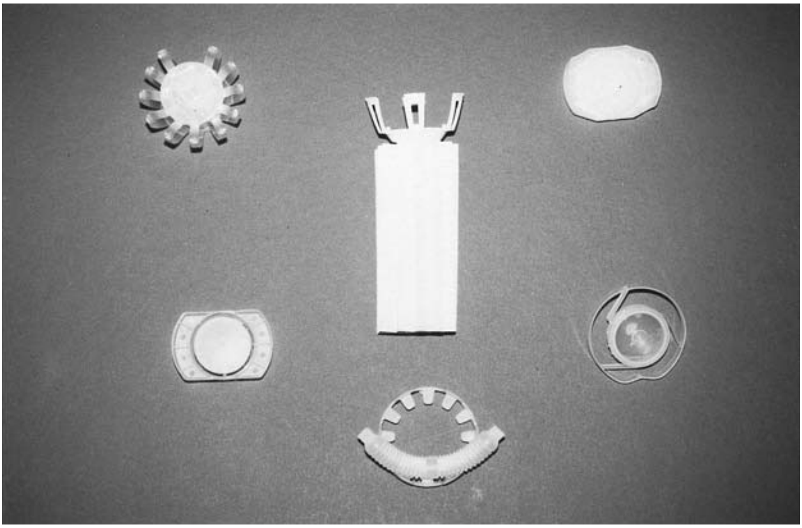


Figure 3.2 *Widgets*
There are diverse sizes and shapes, depending on the Brewer.

levels of up to say 1%, whereas at higher concentrations it is progressively detrimental to foam.

Various physical factors are involved in dictating the rate at which beer foam collapses. As soon as foam has formed, beer trapped between the bubbles starts to drain from it because of gravity. Anything that increases the viscosity of the beer should reduce the rate of drainage. Since viscosity increases as temperature decreases, colder beer has better foam stability. Counter to this is the fact that foam *forms* more readily at higher temperatures, because gas is less soluble.

As liquid drains, the regions between bubbles become thinner, leading to coalescence as bubbles merge into bigger ones. The effect is to coarsen the foam and make it less attractive: foams with smaller bubbles are whiter, with a more luscious consistency in the mouth.

The least desirable set of circumstances occurs if the bubbles in foam are of assorted sizes. The gas pressure in a small bubble is greater than that in a larger one. If two such bubbles are next to one another, then gas will pass from the small bubble to the larger one until the smaller bubble disappears. The result, once again, is a shift to a "bladdery" and unattractive foam. This phenomenon, which is called "disproportionation," happens more quickly at higher temperatures but to a lesser extent if the gas pressure above the liquid is increased. Try covering your beer glass: you'll find that the foam survives longer. This is the principle of the German beer stein, although as steins are generally ornate and the beer can't be seen, the objective is somewhat defeated.

The Physics of Foaming and Flow

Surface tension is the force that holds drops of liquid (such as water) together. The molecules in the liquid are attracted to one another, which drives the tendency to make the surface as small as possible. Therefore, drops are round. Anything that stresses a surface to become bigger (such as foaming) is in opposition to surface tension. As soon as the driving force is removed, surface tension restores the liquid to its original condition.

Viscosity is the resistance of liquids to flow. It is caused by friction between adjacent molecules in the liquid. If the molecules next to one another interact strongly, then viscosity is high. If they don't, then viscosity is low. Honey is a highly viscous liquid; water isn't.

The rate of disproportionation is also lower for gases of lower solubility. For instance, nitrogen is only sparingly soluble in water. Inclusion of just 20–50 mg of nitrogen gas per liter of beer leads to foam with very small bubbles, a foam that is therefore extremely creamy and stable.

Of course, when bubbles are formed in a liquid, the effect is to increase the surface area. This opposes the forces of surface tension, and for this reason pure liquids can't give stable foams. Materials must be present that are able to get into the bubble wall to stabilize it. In beer, the backbone material for bubbles is protein, which comes from the malt. In particular, it is those proteins that have a relatively high degree of "hydrophobicity" (water-hating character) that preferentially migrate into the head. There they encounter other substances with high hydrophobic character, notably the molecules from hops that give beer its bitterness (see hereafter). The interactions between the proteins and the bitter substances hold the bubbles together. This interaction is not spontaneous and proceeds over a period of minutes. As it happens, the texture of the foam changes from being liquid to almost solid, in which state foam can adhere to the glass surface, a phenomenon known as "lacing" or "cling." The longer you delay slurping your beer, the greater the opportunity for the textural transition to occur and therefore the better the lacing.

Just as there are materials in beer that promote foam, there are other substances that interfere with it by getting in between the protein molecules and preventing them from interacting. These materials include ethanol (mentioned earlier) but are primarily lipids (which include fats), which, like the proteins, can originate from the malt. However, good brewing practice should ensure that very low levels of lipids survive in the beer. It is much more likely that these types of substance will get into the beer when it is in the glass and destroy the foam. Any grease or fats associated with food are bad news for beer: if you eat potato chips, the oils associated with them easily kill foam. Lipstick, too, contains waxy substances that will pop bubbles, and the detergents and rinse aids used to wash glasses also tend to be foam-negative. When beer glasses are washed, the detergent must always be washed from the glasses using clean water and the glasses preferably allowed to dry by draining. If the glasses are wiped on a kitchen cloth, it must be a clean one.

Before leaving the topic of foam, we should remember that it isn't always good news. From time to time foaming occurs spontaneously when a can or bottle is opened. In extreme examples, as much as two-thirds of the contents spew forth in a wild and uncontrollable manner. Most people find this to be somewhat irritating. There may be several reasons for the phenomenon, which is called *gushing*. The first, of course, is that the package has been ill treated, dropped, or shaken. Brewers take great care when shipping beer to avoid unnecessary agitation of the beer. And provided a beer is given an hour or two to settle after being dropped or shaken, then the beer won't be wild when the can or bottle is opened.

Unfortunately, gushing is sometimes caused by substances that promote the phenomenon and that originated in the raw materials. Barley grown in wetter climates is susceptible to infection by a fungus called Fusarium. This produces a very small protein molecule that gets into malt and, from there, into beer, where it acts as a very active nucleation site for bubble formation. Another type of molecule, an oxidation product of hops that is found from time to time in certain preparations used to bitter beer, can act in the same way.

Color

An enormous range of colors is found in beers: there are exceedingly pale strawlike lagers, copper-colored ales, rich brown milds, and the blackest of stouts. This wonderful range is seldom achieved by the addition of coloring materials, although caramels have and continue to be used in some quarters for this purpose. Generally the malt and other solid grist materials that are used in the brewhouse determine the color of beer. Recently, however, a new method of coloring beers has been introduced in which the color of dark malts is extracted and separated from the flavor-active molecules in those malts for addition as a liquid late in the brewing process. This extraction process involves making an extract of the dark malt in water and fractionating it according to the size of the substances it contains. This can be achieved using special membranes that allow small molecules to pass through but big molecules to be retained. The components responsible for flavor are small, but the coloring materials are large. Using this technique, then, preparations have become available that enable a beer to be made darker without introducing the smoky/burnt characteristics typical of a roast malt, as well as, conversely, to introduce such flavors into pale beers without making them dark. This presents splendid new product development opportunities to Brewers, as well as an opportunity for introducing color without the use of caramel.

The color-forming materials in the grist are primarily the melanoidins, complex molecules that are produced when sugars and amino acids are heated. The more intense the heating regime, the darker the color produced. Heating is an integral feature of the process by which malt is produced (see chapter 4). The more intense is this kilning, the darker will be the malt. In addition, the more sugars and amino acids present, the greater the potential for making melanoidins. Sugars are formed during the germination of barley when complex carbohydrates (primarily starch) are broken down. Similarly, the amino acids are the end point of protein breakdown. A malt destined for lager production tends to have had relatively limited germination and, more significantly, is kilned to modest temperatures and so the color contribution from it is low. Ale malts are more extensively modified during germination and are kilned to a higher temperature, so they are darker. If the malt is kilned to ever more intense extremes, then profoundly dark malts are obtained (fig. 3.3). Such materials are traditionally employed in the production of darker ales and stouts.

A second source of color in brewing is the oxidation of polyphenol or tannin materials. These tannin-type molecules originate from both malt and hops and are prone to oxidation if large amounts of oxygen are allowed to enter into the brewhouse operations. The reaction involved is exactly analogous to the browning of sliced apples. If this source of color is to be eliminated, it is essential that oxygen must be excluded in the mash mixer and, especially, the wort kettle (see chapter 6).

Haze

Oxidation of polyphenols is much more important for another reason: it results in the formation of haze. In the oxidation process the individual tannin units associate to form larger molecules that associate with protein to form insoluble particles that cause turbidity in beer. The reactions involved are similar to those responsible for the tanning of leather.

Other materials may cause cloudiness in beer. For instance, if the complex carbohydrates of barley, chiefly the starch or the polysaccharides that make up the barley cell walls, are not properly digested in malting and

Figure 3.3 *Malts that have different colors because of different intensities of kilning can be used to produce beers with different colors. Photograph reproduced courtesy of Pauls Malt, Kentford, England.*

brewing, they can precipitate out of beer as hazes or gels, particularly if beer is chilled excessively, for example in inadvertent freezing. Another natural component of malt is oxalic acid, which brewers should ensure is removed in the brewhouse operations by having enough calcium in the water to precipitate it out. If they fail in this task then the oxalic acid will survive into beer. This is primarily a problem for draft beer because oxalate will precipitate out in the dispense lines and clog them. This is called "beer stone."

Flavor

The flavor of beer is no simple affair. There are the obvious tastes one associates with the product, in particular the bitterness imparted by hops. And, as for most foodstuffs, the characters of sweet and salt play a part, although few desirable beers have sourness among their attributes. A wide range of volatile substances contributes to the aroma of beers, including esters, sulfur-containing compounds, and essential oils from hops. Ethanol itself provides a warming effect and seems to influence the extent to which other molecules contribute to a beer's character. Even carbon dioxide has a role to play.

To complicate matters further, it should be appreciated that the flavor of beer is not static. From the time that fermentation is complete to the moment that the beer is packaged, changes occur in its taste and aroma. And it doesn't stop there: just as with wine, the character of beer changes in the package. Only rarely are these changes for the better in beer, as we shall see.

The Nature of Beer Flavor

The flavor of a beer can be broken down into its taste, smell (aroma), and mouthfeel (texture or body). Brewers also talk about "flavor stability," in reference to the deterioration in quality as the beer ages in package.

Taste. The bitterness of beer is due to a group of compounds called the iso-α-acids that originate from hops (see chapter 5). There are six different iso-α-acids, which differ in their relative bitterness impact. The perceived bitterness of a beer, therefore, depends not only on the overall level of these iso-α-acids in the product but also on the relative proportions of each of the six so-called isomers. This, in turn, is dependent on the variety of hop from which the bitterness is obtained and on the manner by which it is processed before it is used in the brewery. To add to the complication, a drinker's perception of bitterness changes with time after the first sip of beer is taken. There is an initial perceived bitterness, followed by a gradual subsidence of the effect.

In fact, the ability of a drinker to estimate the bitterness of a beer is generally fairly poor. A well-trained taster may be able to address the problem, but everybody else will tend to have his judgment clouded by other features of the beer, most notably sweetness.

The sweetness of beers is due to residual sugars that have not been fermented into alcohol. Frequently the Brewer will add sugar ("primings") to the beer before packaging. Beers vary enormously in their relative sweetness, indeed in their bitterness-sweetness balance.

Although "salty" is not a word that many people would use to describe beer, certain salts do contribute to beer flavor. In particular the ratio of chloride to sulfate is felt by some to be important. Sulfate is claimed to increase the dryness of a beer, while chloride is said to mellow the palate and impart fullness. The importance of this chloride-to-sulfate ratio is one example of the plethora of dogmatic beliefs held by many brewers. In fact, there is little if any published scientific data to justify the conclusions made concerning this ratio—which is not to say that it is not important but rather that, if it were in the dock in a court of law, it wouldn't have much of a hard-and-fast defense.

Other ions are certainly significant. For example, traces of iron that might be picked up from the materials used to filter beer will give an unacceptable metallic character to a product.

Aroma. The taste and the smell of a foodstuff such as beer are very closely related sensory phenomena. What a drinker will generally describe as the "flavor" of a beer is in reality character that is actually detected in the nasal passages: it is, strictly speaking, defined as aroma. If you have suffered from a head cold and have blocked nasal passages, you will appreciate the effect that this can have in eliminating the sense of taste.

Whereas relatively few substances contribute to the true *taste* of beer (bitter, sweet, salt, sour—see earlier), many different types of molecule influence aroma. Lots of these are produced by yeast during fermentation. There are alcohols other than ethanol, which can impart coconut or solventy characters, and there are aldehydes, which give aromas like green leaves. Principally, though, there are the esters, the short-chain fatty acids, and many of the sulfur compounds. The pH of beer is also largely dependent on fermentation, as yeast acts to lower the pH of wort from 5.2–5.5 to 3.8–4.5.

The pH of beer has enormous influence on product quality. Many of the molecules in beer can exist in charged and uncharged forms, the relative proportions of which are directly dependent on the pH. For instance, the bitter compounds exist in both uncharged and charged states, and the former is bitterer than the latter. The hydrogen ions that cause a beer to be acid (low pH—see the appendix) impart sourness. That is, if a beer has a low pH (say 3.8) it will be sourer than one that has a pH of 4.5.

A selection of esters is present in beers. These vary in the type of flavor they impart (table 3.1). It is the mix of esters and other volatile compounds that determines the aroma of beer. Drinkers might say that a beer is "fruity" or even that it tastes like "bananas," but its true character is seldom so simple as to be traceable to just one or even a very few types of flavor molecules. Rather it is the combined effect of a complex mixture that will determine overall "nose." Such complexity ensures that individual beers are unique, but it also makes considerable demands on the Brewer if consistency is to be ensured.

Esters, then, have a range of individual aromas in the pure state, which aren't simply related to the character these substances impart to the complex matrix that is beer. The same applies to other classes of compound found in beer. For instance, various sulfur compounds may be present (table 3.2). Comparison of the flavor descriptors and flavor thresholds of the sulfur compounds with those of the esters indicates why Brewers are often rather more worried about the former.

Table 3.1
Some of the Esters That Can Be Found in Beer

Ester	*Flavor descriptor*	*Approximate flavor threshold (ppm)*[a]
Ethyl acetate	Solvent, fruity	30
Butyl acetate	Banana, sweet	7.5
Isoamyl acetate	Banana, apple	1
Ethyl valerate	Papaya	1
Isoamyl propionate	Pineapple, aniseed	1
Ethyl nicotinate	Medicinal	6
Phenylethyl acetate	Roses, honey	4
Methyl caprate	Coconut	1
Octyl caproate	Orange peel	5
Isoamyl caprate	Tropical fruits	3

Source: M. C. Meilgaard, *Technical Quarterly of the Master Brewers Association of the Americas,* 12 (1975), pp. 151–168.
[a]The flavor threshold is the concentration of a substance that must be present in a beer before it can be detected.

One prominent sulfur compound, present in many lager-style beers, is dimethyl sulfide (DMS); it is a remarkable molecule, found throughout nature. Apart from finding it in lager, you might detect it in baby's breath and cat's urine! It is also prominent in the smell of parsnips, tomato ketchup, black currants, and sweet corn.

Brewers differ in their preference for having DMS in their lagers. Some like it, generally in the range of 40–100 ppb, and there are certainly a good many lagers across mainland Europe that have a character substantially de-

Table 3.2
Some of the Sulfur Compounds That Can Be Found in Beer

Sulfur compound	*Descriptor*	*Approximate flavor threshold (ppb)*
Ethyl mercaptan	Rotting leek, onion, garlic, egg	2
Dimethyl sulfide	Cooked vegetable, corn, blackcurrant	30
Diethyl disulfide	Garlic, burnt rubber	0.5
Amyl mercaptan	Rotting guava; cat urine	0.0001
Methional	Mashed potato	250

Source: M. C. Meilgaard, *Technical Quarterly of the Master Brewers Association of the Americas,* 12 (1975), pp. 151–168.

termined by DMS at these (sometimes even higher) levels. Other brewers are adamant that DMS is an "off" character that must be maintained at levels below its flavor threshold of around 30 ppb.

To control DMS in lager to a defined level is a remarkable feat (see chapter 6). However, even if DMS is controlled to the desired level, there is still a problem, and it is one that illustrates nicely the thesis that the aroma of beer is the net result of the contribution of a whole range of compounds. It has been shown that even expert tasters given a wide range of beers to taste can't correlate perceived DMS character with the level of DMS measurable in those beers. Amazingly, they *could* detect a decrease in perceived DMS character as the level of phenylethanol (rose flavor) in beers increased. For beers of similar phenylethanol content, there is a direct link between actual DMS and the ability of tasters to detect it. In other words, some compounds are able to suppress the extent to which other compounds can be detected. Equally, it is believed that other compounds interact cumulatively, or at least additively, in their effect on flavor. For example, several compounds may individually be present in beer at levels below their flavor thresholds but "combine" to provide a discernible character, presumably because they each react at the same location in the olfactory system.

Short-chain fatty acids generally provide undesirable characters to beer. Descriptors include cheese, goat, body odor, and wet dog! Happily for the drinker, the Brewer's control over the process means that undesirable levels of this type of compound seldom find their way into the beer.

Just as undesirable is the character introduced by the so-called vicinal diketones. Diacetyl, the most important of these, has an intense butterscotch flavor. Few of us like our beer to taste of candy!

Diacetyl is naturally produced in all brewery fermentations. It is an offshoot of the metabolic pathways that the yeast uses to make some of the building blocks that it requires for growth. The diacetyl leaks out of the yeast cell and into the fermenting broth. Happily, yeast is also capable of mopping up the diacetyl again. And so, toward the end of fermentation, the yeast scavenges the diacetyl and converts it into substances that do not have an intense aroma. To do this the yeast must be in a healthy state, but even then the process can take a considerable period of time. Thus the period for which a beer must stay in fermenter depends not only on the time taken to convert sugar into alcohol but also on the additional days required to eliminate diacetyl and take it below its flavor threshold, which is unlikely to be greater than 0.1 ppm and can be considerably lower for some of the more gently flavored lagers.

Another undesirable flavor in beer is acetaldehyde, which imparts a character of green apples. Surpassing all others in the "undesirable flavor stakes," however, is the aroma imparted by a compound called 3-methyl-2-butene-1-thiol (MBT). It is produced through the degradation of the iso-α-acid bitter substances, a breakdown that is brought on by light. People differ in their sensitivity to MBT, but for many it can be detected at levels as low as 0.4 parts per trillion. To put this into perspective, these poor people would have been able to detect a tenth of a gram of MBT distributed throughout the balloon of the airship *Graf Zeppelin II*.

The aroma that MBT imparts is referred to either as "lightstruck" or, worse still, "skunky." Brewers have known about the problem for many years, and it is the reason that beers need to be protected from light. Brown glass is better than green glass in this context. Clear, flint glass is the worst option. An alternative strategy is to use modified (reduced) iso-α-acids that, when broken down, no longer give MBT. The added advantage is that this reduction increases the hydrophobicity of these molecules and therefore enhances their foam-stabilizing properties, although the texture and appearance of such foams is viewed by many as being artificial.

It's high time to return to some of the more desirable characters in beer. Generally these originate from the malt and hops. Malty character is quite complex and is due to a range of chemical species. Hoppy character, too, is far from simple and may, indeed, take various forms. It is due to the essential oils of hops, but the contribution they make to aroma differs considerably among beers.

For the most part, the hops are added at the start of the boiling process, and because the essential oils, being volatile, are comprehensively driven off during the boiling operation, the resultant beers, while bitter, have no hoppy character. As mentioned in chapter 2, some Brewers practice "late hopping" and "dry hopping" to introduce hoppy character.

Flavor Balance. This is an appropriate point to emphasize that beer flavor is not simply a matter of introducing greater or lesser quantities of a given taste or aroma into a product, depending on the character desired in a given product. A beer is pleasing, interesting, and, above all, *drinkable* because it has its various organoleptic properties in balance.

If I were to have a single criticism of some of the beers being produced by microbrewers, it would be that they have failed to grasp this point. Many of these Brewers seem to have overdosed on hops, rendering their beers intensely aromatic and, of course, extremely bitter. It is perfectly satisfactory to have a very bitter beer—many such products of long standing exist in the world. Equally, there are many leading brands of lager that have pronounced late hop character but modest levels of bitterness. I have discussed how aroma and bitterness levels in beer can be independently adjusted, enabling products with excellent *balance*. Just as for hop-derived characters, so too must parameters such as sweetness-bitterness, volatiles, and so on be balanced. A high level of DMS may be utterly unacceptable in one product, whereas in another it may be warranted because it offsets or complements a characteristic introduced by a different component.

The myriad of interactions that may take place in the human taste and olfactory system following the consumption of beer is enormously complicated. Certainly there is only limited knowledge of the physiological basis for them. Yet it is perfectly possible, indeed essential, for the Brewer to design products that delight the consumer because their flavor characteristics are so carefully balanced, with or without high overall flavor impact. These are the products that a consumer will find drinkable and will be tempted to order again. Overtly flavored products undoubtedly interest, and are enjoyed by, some consumers, but the biggest-selling brands worldwide tend not to have extremes of taste or aroma.

Mouthfeel. One of the least understood aspects of beer flavor, mouthfeel, is sometimes referred to as body or texture. Recently a vocabulary to describe what expert tasters perceive as mouthfeel has been developed. One of the terms is “tingle,” which is quite clearly directly related to the carbon dioxide content of a beer. Carbon dioxide reacts with pain receptors in the palate (leave your tongue in a highly carbonated beer for a few minutes, and you’ll see what I mean), yet most people find this sensation pleasurable. For many beers a relatively high concentration of CO_2 is essential to deliver this effect, which results from contact with the trigeminal nerve. In the United States, most beers are relatively highly carbonated (in excess of 2.6 volumes CO_2 per volume of beer). However, English ales traditionally have had low carbon dioxide content, and a new genre of low CO_2 keg ales has sprung up in recent years. These are the “nitrokegs,” so named because the beer also contains nitrogen both to support foam qualities and to impart the textural smoothness long known to be associated with use of this gas. The downside for some Brewers is that the use of nitrogen suppresses hoppy nose—one more example of how one aspect of beer quality influences another.

Nobody is certain of all the chemical species in beer that might influence texture. Some say the long and wobbly polysaccharides (the β-glucans) originating in the cell walls of barley have a role. Certainly they will increase viscosity, and some people suspect that increased viscosity is an important contributor to mouthfeel, as it will alter the flow characteristics of saliva in the mouth. Others have championed proteins, chloride, glycerol, organic acids (such as citric acid and acetic acid), and even ethanol itself as determinants of mouthfeel. Some believe that the polyphenols that I referred to earlier are important. They have long been known to cause astringency in ciders, and astringency is certainly one term in the mouthfeel vocabulary, but the levels of tannin found in beer are substantially lower than those in red wine or hard cider.

Flavor Stability. While flavor is conveniently described in terms of the individual components of a freshly packaged beer, the quality of beer most definitely changes over time. Such changes will be much more readily apparent in the more subtly flavored lager-style products. The nature of the changes differs between beers but will generally include a decrease in bitterness and increase in sweetness, the development and subsequent decline (thank goodness) of a ribes character (blackcurrant buds, tomcat pee), and the development of a cardboard or wet paper note, followed by winey, woody, and sherry-like characteristics.

Despite years of extensive research, there is no consensus among brewing scientists regarding the origin of the carbonyl compounds that cause this phenomenon. Some champion the bitter compounds, the iso-α-acids, as being a prime source. Others believe that certain higher alcohols that are produced by yeast during fermentation are important. The majority believe that the staling of beer, just like that of other foodstuffs, can be traced to the oxidation of unsaturated fatty acids, notably linoleic acid, that originate in the malt.

What is certain is that the degradations that lead ultimately to the development of staleness depend on the presence of oxygen. For this reason it is essential during packaging to minimize the ingress of oxygen into the can, bottle, or keg. Furthermore, oxygen uptake into the package in trade must be avoided. This is only really significant in bottled beers, where oxygen can sneak in through the seal between the crown cork and the neck of the bottle. Recently some Brewers have used corks that have an oxygen scavenger melded into them.

Despite the precautions taken to avoid oxygen access to beer in the package, all beers stale eventually. There is an increasing conviction that the tendency to form this cardboard character is built into the product during the production process. And so Brewers have started to consider eradicating oxygen uptake throughout the brewery and have even started to suspect that the oxidation reaction has already started in the malting operation. (An unwritten rule for too many Brewers is "pass the buck and blame the maltster"—as often as not this is unjust.) The reason these carbonyl compounds don't reveal themselves during the process may be that oxidation only goes as far as an intermediate that subsequently breaks down in the package over time. Alternatively, it may be that the staling compounds are produced early in the process and bind onto other compounds (principally sulfur dioxide, which is a natural product of fermentation, and amino acids) and that the complexes thus formed degrade progressively in the beer, exposing the carbonyl character.

Like other chemical processes, the staling reaction is retarded at reduced temperatures. A can of beer on an unrefrigerated shelf in Death Valley will stale in a couple of days, whereas the same beer in a refrigerator will still be fresh six months later. In some markets, notably the States, refrigerated distribution is widely employed.

Beer as a Foodstuff

Is Beer Good for You?

For many years Guinness advertised its beer on a platform of *Guinness Is Good for You,* before changes in law decreed that this type of claim could no longer be made. Later, also in the British Isles, came claims (less overt ones perhaps) for another beer: *A Double Diamond Works Wonders.* A Shakespearean actor, Sir Bernard Miles, was featured in a television campaign extolling the virtues of Mackeson stout, using the immortal lines: *It looks good, it tastes good, and by golly it does you good!* Nowadays there is little doubt that the first two claims, regarding appearance and flavor, could still be fair game in a television advertisement. The problem would come with the third; It is no longer legitimate to make claims that beer drinking is good for you. Nonetheless, there is growing scientific evidence in support of such statements. Beer truly is "liquid bread"—and rather more besides.

Of course, a broad spectrum of opinion exists concerning the desirability of consuming alcoholic beverages. For millions worldwide, such drinks are condemned on religious grounds. Among cultures where alcohol is tolerated, right-minded individuals recognize the social unacceptability of consuming alcohol to excess, with the terrible price it can have for some through road traffic accidents and family distress and for others through the development of conditions such as cirrhosis of the liver and certain types of cancer. This is quite apart from the impairment of performance that drinking at inappropriate times can cause. Increasingly, however, it is becoming recognized that there may be some health benefits associated with the consumption of alcoholic beverages in moderation—and not only by helping to reduce stress and stress-related problems such as increased excitability and heart rate.

The health-related uses of beer go back to ancient Egypt, where it was used as a mouthwash, enema, vaginal douche, and applicant to wounds, quite apart from its importance as a key component of the diet. It seems that on Captain Cook's ships, beer contributed as many calories to the sailors' diets as biscuits and meat combined. Perhaps John Taylor, who kept an alehouse in London, England, penned the most glowing description of the benefits of drinking beer. In 1651 he suggested that beer

> is a singular remedy against all melancholic disease, tremor cordis and maladies of the spleen; it is purgative and of great operation against Iliaca passio, and all the gripings of the small guts; it cures the stone in the bladder, reines [or kidneys] and provokes urine wonderfully, it mollifies tumours and swellings on the body and is very predominant in opening the obstructions of the liver. It is most effectual for clearing of the sight, being applied outwardly it assuageth the unsufferable pain of the Gout called Artichicha Podagra or Ginogra, the yeast or barm being laid hot to the part pained, in which way it is easeful to all impostumes, or the pain in the hip called Sciatica passio . . . and being buttered (as our Gallenists well observe) it is good against all contagious diseases, fevers, agues, rheums, coughs and catarrhs.[1]

That's quite a testimony. I can say, with rather more careful consideration and supportive evidence, that there are indeed potentially positive aspects to the drinking of beer.

In comparison with other alcoholic beverages, the content of alcohol is relatively low in the majority of beers. The alcohol strength of beers, which for the most part tends to be in the range of 3–6% by volume, is much lower than that of most other alcoholic drinks. Beer, then, is more suited to the quenching of thirst and counteraction of dehydration than wine, for instance. In some countries (such as Germany) beers at the lower alcohol end of the spectrum are favored as sports drinks, because their osmotic pressure is similar to ("isotonic" with) that of body fluids. Such beers do possess some calorific value as an energy source, because they do contain some carbohydrate, as well as ethanol. Incidentally, all beers are, to all intents and purposes, fat free.

It has been claimed that beer (though not the alcohol within it) stimulates milk production in nursing mothers and may reduce the risk of gallstones and promote bowel function—it has even been claimed in Japan that materials that are produced during the kilning of malt and that enter into darker beers suppress the onset of dental caries!

Beer contains some vitamins, notably some of those in the B group (pyridoxine, niacin, and riboflavin, and, above all, folic acid), and minerals, especially magnesium, potassium, and selenium. Beers generally have a low ratio of sodium to potassium, which is beneficial for blood pressure. There are usually quite high concentrations of calcium and phosphate in beer and also of silicic acid, which supposedly promotes the excretion of potentially harmful aluminum from the body (aluminum being one of the purported causative agents in Alzheimer's disease).

Recently a number of publications have drawn attention to the importance of antioxidants in foodstuffs and the possible contribution these could make to the diet, in terms of protecting against oxygen radicals, which are understood to have undesirable influences on the body. Most significant of these antioxidants are the polyphenols, which are present, inter alia, in beer. They may also include ferulic acid. Incidentally, in the case of ferulic acid (and silicon), it has been demonstrated that it is "bioavailable"—it actually does get into the body and, presumably, gets to do the good that is claimed for it. All too often it is not clear that the supposedly beneficial constituents of foods even get assimilated into the body. Consideration of all these benefits from drinking beer (and see table 3.3) then makes it small wonder that, for generations, stouts were a recommended part of the diet of nursing mothers. These days, of course, pregnant women are much more likely to be dissuaded from consuming alcohol in all forms, for fear of harm to unborn infants.

Most debate in recent years has focused on the relative merits and demerits of consuming ethanol itself for the broader adult populace. Evidence emerging from the medical community that moderate drinking correlates with lower death rates from various causes led a few years ago to the United Kingdom government raising its recommended maximum for drinking by adults: men are advised to drink no more than 26 units a week (a unit in the U.K. is 8 g of alcohol, which is roughly equal to half a pint of medium-strength beer) and women no more than 21 units. In addition, the advice is to consume no more than 4 units per day. Compare this with the recommendations of the French, whose more liberal attitude to alcohol and predilection for wine prompts them to advise men to drink no more than one bottle of wine per day, and women no more than half a bottle.

In particular there seems to be evidence for alcohol protecting against cardiovascular disease. These effects may be linked to a component of beer other than alcohol itself, but ethanol may alter the balance of the high- and low-density lipoproteins in the blood, such that the deposition of fats on artery walls is reduced. Alcohol also appears to reduce the "stickiness" of blood platelets, making them less likely to aggregate together as blood clots.

Another component of beer that may have a hypocholesterolemic influence is the β-glucan, which is the principal component of the cell walls of barley and can cause all sorts of problems for the Brewer (see chapter 6). However, if this polysaccharide survives into beer, it represents soluble fiber, which has been claimed to have a cholesterol-lowering effect.

Wide ranges of clinical studies have concluded that there is a "U-shaped" relationship between deaths and alcohol consumption (fig. 3.4). Modest consumption of alcohol lowers the relative risk of death, particularly

Table 3.3
The Composition of Beer Relative to Recommended Dietary Intakes

Parameter	*Daily adult (age 25–50) requirement*		*Range in beer (per liter)*
	Male	*Female*	
Energy (Kcal)	2550	1940	150–1100
Protein (g)	63	50	3–5
Carbohydrate (g)[a]	—	—	0–61
Fat (g)[a]	—	—	Neg
Vitamin A (μg)	1000	800	Neg
Vitamin D (μg)	5	5	Neg
Vitamin E (mg)	10	8	Neg
Vitamin K (μg)	80	65	Neg
Vitamin C (mg)	60	60	Up to 30
Thiamine (mg)	1.5	1.1	0.003–0.08
Riboflavin (mg)	1.7	1.3	0.02–0.8
Niacin (mg)	19	15	3–8
Vitamin B_6 (mg)	2.0	1.6	0.07–1.7
Folate (μg)	200	180	40–600
Vitamin B_{12} (μg)	2	2	3–30
Biotin (μg)	30–100	20–100	2–15
Calcium (mg)	800	800	40–140
Phosphorus (mg)	800	800	90–400
Magnesium (mg)	350	280	60–200
Potassium (mg)	3,500	3,500	330–1100
Sodium (mg)	1,100–3,300	1,100–3,300	40–230
Iron (mg)	10	15	0.1–0.5
Zinc (mg)	15	12	0.01–1.48
Selenium (μg)	70	55	<0.4–7.2

Source: C. W. Bamforth, "Nutritional Aspects of Beer–A Review," *Nutrition Research* 22 (2002), pp. 227–237.
Note: "Neg" means negligible.
[a]For a diet containing alcohol the recommendation is that the population average should have 15% of total dietary energy in the form of protein, 47% as carbohydrate, and 33% as fat.

through a lesser incidence of coronary heart disease. This relationship appears to hold across national boundaries and cultures and was most famously publicized as the so-called French paradox: a people famed for their enjoyment of fine food high in saturated fats leading to high levels of cholesterol in blood serum nonetheless reported some of the lowest frequencies of deaths from coronary heart disease. Hence we see a justification for their relatively high recommended alcohol intake, although it has also been suggested that it is not only the alcohol in drinks that has a beneficial effect but also other components of the so-called Mediterranean diet, such as garlic.

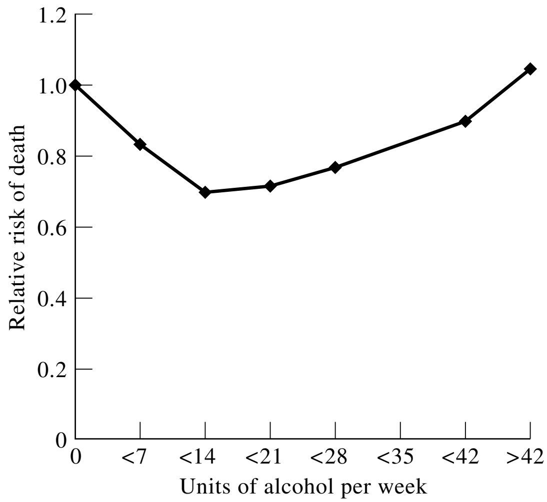


Figure 3.4 *The "U-shaped curve." Several independent studies have all generated a profile similar to this one, which is adapted from an article by Denise Baxter (*The Brewer *[February 1996], pp. 63–66). Indeed the first report of such a U-shaped curve was made in 1926 by R. Pearl in a book entitled* Alcohol and Longevity *(New York: Knopf). Since that time studies in Britain, Japan, Denmark, and America have all demonstrated this type of profile, with particular emphasis on coronary artery disease. An excellent review of this topic was penned by Dr. Tim Cooper (T. J. Cooper, in Medical Considerations of Moderate Alcohol Consumption* Proceedings of the Twenty-third Convention of the Institute of Brewing, Asia Pacific Section *(East Brisbane, Qld, Australia: Institute of Brewing, Asia Pacific Section, 1994) pp. 32–37. See also my own article, "Nutritional Aspects of Beer—a Review,"* Nutrition Research 22 *(2002), pp. 227–237.*

Some authors argue for a superior beneficial effect of alcohol when taken in the form of red wine rather than beer. It seems however that most if not all of these studies have failed to take into consideration confounding factors in the diet. Merely to compare wine drinkers with beer drinkers and to ignore the other elements of their respective lifestyles is misleading. Exaggerating to make the point, we might say that wine drinkers eat lettuce leaves, work out at the gym, and occupy higher socioeconomic strata (with enhanced access to health care) compared with beer drinkers, who stuff burgers and watch ball games as couch potatoes. Incidentally, in nineteenth-century England, teetotalers were regarded as cranks who were jeopardizing their health by ignoring beer, which was considered to be a key feature of the diet.

In summary, it does very much seem that there may be benefits associated with the moderate consumption of alcoholic beverages, including beer, by mature and well-adjusted adults, at the appropriate time and in the appropriate place. Drinking to excess always has been and always will be antisocial, dangerous, and unacceptable. Back in 1789 James Madison expressed the wish that "the brewing industry would strike deep root in every state in the Union." The concern was about the growth in consumption of hard liquors—to the extent that in Massachusetts a law was introduced exempting breweries from excise taxes for five years. The legislature said that "the wholesome qualities of malt liquors greatly recommend them to general use as an important means of preserving the health of the citizens of this commonwealth."

Why Beer Can Be Safer to Drink Than Water

Beer is most inhospitable to the growth of microorganisms. The boiling stage in beer production kills the vast majority of organisms that might have entered into the process. During fermentation the pH falls to about 4.0, which is too low for most organisms to thrive, and, of course, most of the nutrients that a contaminating microbe would need are efficiently consumed by yeast. At the same time, ethanol is produced, which itself protects against microbial growth. Most beer is packaged under relatively anaerobic conditions, preventing the growth of any microbe that requires oxygen. And it has been proven that those pathogenic bacteria that don't require oxygen are unable to populate beer. Above all, beer contains various substances that suppress bacterial growth. These include some of the tannins, but in particular it is the bitter compounds, the iso-α-acids, that have a profound antimicrobial influence. (What wonderful things these substances are: they make beer nicely bitter, they help provide the foam, and they prevent bug infections—what a pity they are the cause of skunky flavor!)

Beer Strength: Its Relevance

The strength of a beer is defined by its alcohol content. Typical alcohol levels for a range of alcoholic beverages are shown in table 3.4, together with the

Table 3.4
Typical Alcoholic Strengths of Various Beverages

Drink	*Typical alcohol content (% ABV)*	*Volume of drink constituting a "unit"*
Premium beer	4.5	approx. half a pint
High-strength beer	9.0	approx. quarter pint
Wine	12.0	approx. 1/7 of a 75 cl bottle
Whiskey	40.0	approx. 25 ml
Gin	40.0	approx. 25 ml
Vodka	45.0	approx. 20 ml

volume of each drink that constitutes a "unit."At one extreme can be found beers containing more than 13% alcohol by volume. At the other pole are the alcohol-free beers. Quite apart from the obvious variation in physiological impact that beers of different alcoholic strength will have, the alcohol influences flavor, directly and indirectly, as well as the foaming properties of beer, as we have seen.

Perhaps most important, though, is the fact that in many countries, the tax is levied on the basis of alcoholic strength. This is not the case in the United States, where fixed rate levies are made at federal and state levels on a per barrel basis, irrespective of the strength of the beer in the container (see chapter 1). In the United Kingdom, the amount of duty levied is in direct proportion to the alcohol content of the beer (see chapter 9). Small wonder that the precision with which alcohol content of beer can be measured is most important, both to the Brewer and to Her Majesty's Customs and Excise. Indeed, in all countries, it is most important that careful checks and records are made of volumes of beer, because that always has a direct impact on the size of the check that the Brewer will be writing to the taxman.

Thus, a vast myriad of compounds and physical interactions influence the quality of beer. Let just one of them be out of balance, and the whole product will be ruined. Time now, then, to walk steadily through the malting and brewing processes to see how it is that the devoted Maltster and Brewer strive to ensure that the balance in your beer is indeed right, time after time after time.

4

The Soul of Beer

Malt

More than 90% of the beer brewed worldwide has barley malt as the key grist component. True, some beers, such as the weissbiers in Germany, are produced from malted wheat, and the so-called kafir beers in South Africa are based on sorghum. Many malt-based beers contain other grist materials, often for reasons of cost, but also because they may introduce distinctive characters. Thus a major international brand features rice in its recipe, and some Brewers will use wheat-based adjuncts because they feel they enhance foam quality. These so-called adjuncts will be considered in chapter 6.

It is malted barley, though, that remains the foundation of most beers, and it seldom accounts for less than 50% of the grist. Frequently it will be the sole source of fermentable carbohydrate. Efficient brewing and top-quality beer is inextricably linked to the quality of the malt. Both the quality of the barley and the malting operation must be right.

Barley

Cultivated barley (*Hordeum vulgare* or *Hordeum distichon*) belongs to the grass family (the *Gramineae*) and is grown in more extremes of climate than any other cereal (table 4.1). It has been estimated that barley emerged from its ancestor in Egypt some 20,000 years ago. Worldwide production of barley is now in excess of 170 million tons, but less than 25% of that is malted for the brewing of beer.

Table 4.1
World Barley Production

Country	*Barley grown (million tons)*
Russia and the countries of the former Soviet Union	48
Germany	14
Canada	13
United States	11
France	10
United Kingdom	10
Spain	9
China	6
Turkey	6
Denmark	5
Australia	4
Poland	4
Remainder	*34*

Source: Based on C. W. Bamforth and A. H. P. Barclay, *Malting Technology and the Uses of Malt,* edited by Alexander W. MacGregor and Rattan S. Bhatty (St. Paul, Minn.: American Association of Cereal Chemists, 1993), pp. 297–354.
Note: Figures are rounded averages of production over a 10-year time frame.

Barley can be identified in the field by its characteristic whisker, or awn (see fig. 2.1). Two types of barley are used for malting and brewing. In two-rowed barley, two rows of kernels develop, one on either side of the ear. Six-rowed barley has three corns on either side of the ear. Space is restricted on the ear, meaning that some of the corns in the latter type must be twisted in order to fit. Six-row barleys may have a higher proportion of cell-wall material in their endosperms that must be efficiently dealt with if problems are to be avoided in the brewery, and they are generally capable of producing higher levels of enzymes.

The barley corn consists of a baby plant (embryo), together with an associated food reserve (starchy endosperm), packed within protective layers (see fig. 2.3). It is the food reserve that is of primary interest to the Brewer (and therefore the Maltster), as this is the origin of the fermentable material that will subsequently be converted into beer. The reserve consists of starch in the form of large (type A) and small (type B) granules, packed within a matrix of protein, and the whole is wrapped up in a relatively thin cell wall (fig. 4.1). The cells of the starchy endosperm (barley corns contain approximately a quarter of a million of them) are dead, and, although they contain

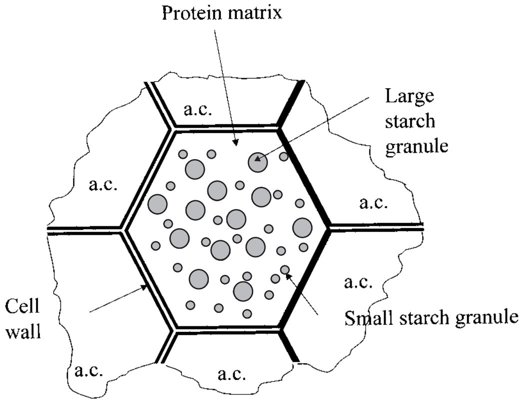


Figure 4.1 *A schematic representation of a cell in the starchy endosperm of barley. The walls (indicated by the dark black line) comprise different types of polysaccharide, while the area between adjacent cells (a.c.) is called the "middle lamella" and is made of protein. Protein is also found inside the cells, where it surrounds large and small starch granules. The starch granules are illustrated only for the central cell in this diagram. In reality there will be many more of these per cell.*

a few enzymes, most of the significant enzymes that are necessary to digest the food reserves can't be made by the starchy endosperm.

It is the embryo that has ultimate control on the breakdown of the endosperm. After all, this is *its* food reserve, the true function of which is as a source of nourishment to support its growth. The endosperm wasn't designed to oblige the Maltster or Brewer! The skilled maltster takes advantage of the embryo's ability to mobilize its foodstore to enable him to furnish the Brewer with good-quality malt.

The embryo itself is capable of some enzyme synthesis, through the region known as the scutellum. Primarily, though, it is believed that enzyme production is the preserve of the aleurone tissue, which is two to four cells deep and surrounds the starchy endosperm. The embryo produces a series of hormones, which migrate to the aleurone, there to control the switching on or off of enzyme synthesis. The hormones called gibberellins largely promote the development and release of enzymes, which is antagonized by another hormone, called abscisic acid. It seems that it is the balance of these different hormones that regulates the extent to which the various enzymes are produced.

Before an embryo can leap into action and produce these hormones and before any enzyme can act to hydrolyze the starchy endosperm, the barley's moisture content must increase. Whole barley from a malting store will typically contain some 10–13% water, with the embryo holding 18–20% moisture. To commence metabolism of the embryo, this moisture content must be increased. The starchy endosperm, too, must be hydrated, for enzymes act more rapidly if their substrates are solvated.

In the malting process, then, barley is first steeped in water, to bring it up to a moisture content in the region of 42–46%. This triggers the synthesis and migration of enzymes into the starchy endosperm. The first enzymes produced are those that open up the cell walls and hydrolyze their constituents. Following on from these are the proteolytic enzymes, and the last enzymes to be made are the amylases, which are responsible for degrading the starch.

A major requirement in the production of malt for brewing is comprehensive hydrolysis of the cell walls, which leads to a softening of the grain and its easier milling and extraction. Second, there needs to be a substantial breakdown of protein, to eliminate potential haze-forming material and to release foaming polypeptide but primarily to produce amino acids, which the yeast will require as building blocks to make its own proteins and therefore grow. What the brewer does not want is significant degradation of the starch, for it is this that she wants to break down in the brewery to yield fermentable sugars.

The germination of barley, therefore, is carried out for a time sufficient to degrade cell walls and protein and for starch-degrading enzymes to be synthesized but not long enough to lead to excessive growth of the embryo. The process is generally referred to as "modification." Once modification is completed to the required extent, it is halted by kilning.

Which Barley?

Any barley, providing it is living (viable), can be malted, but the quality of the malt and the efficiency of the malting operation depend greatly on the nature of the barley. In turn, this makes certain demands of the farmer.

Barleys can be divided into so-called malting and nonmalting (or feed) grades. The division is based on the amount of extractable material that can be obtained from their malts in a brewing operation. Malting varieties give high levels of extractable material, nonmalting grades don't—or, more accurately, they don't when malted for conventional periods of time and brewed in a conventional matter.

The difference between barleys lies in the ease with which their endosperms can be modified during germination. In nonmalting grades, substantial areas of the endosperm will remain intact after conventional periods of germination (four to six days). This may be because water doesn't get distributed evenly throughout the endosperm, which in turn must have something to do with their structure. Alternatively, their cell walls may be less easily degraded than those of better grades, or they may be less capable of synthesizing enzymes.

Evidence suggests that all of these factors may be important. Feed-grade barleys have a relatively high proportion of corns that have "steely" endosperms, in which the components are very tightly packed, which means that neither water nor enzymes can easily gain access. Malting barleys, however, have more "mealy" endosperms, which distribute water easily and are readily accessed by enzymes.

Steely endosperms *can* be hydrolyzed; it merely takes longer than for mealy grain. Like the Brewer, the maltster works to tight time frames and will ordinarily select barley varieties of the higher malting grades. Indeed, the Brewer in turn is likely to insist on given varieties. Given the choice of two malts that possess identical analyses, many Brewers will opt for a variety they know, because unexpected problems might occur with unproven varieties.

New varieties are continually coming into the marketplace as the end product of plant breeding; with similar rapidity, older varieties disappear. Each variety has its own name, and there are some rather colorful ones. For many years varieties such as Plumage Archer, Maris Otter, and Proctor led the way in the United Kingdom, and they were relatively long lived, in that they were used year after year by Brewers who were convinced of their importance in the brewing of top-quality ales. Indeed, there are still a few Brewers who swear by Maris Otter today—and malts made from this variety are very popular with the microbrewers in the United States. These days you'll find many more varieties in the United Kingdom, including winter varieties such as Regina and Fanfare and spring cultivars such as Chariot and Optic. It is extremely unlikely that they will have as long a life as Maris Otter, the current fashion being for change. In the States there are six-row varieties, including Excel, Stander, Robust, and Morex, and two-row varieties including Harrington, Garnet, and the less fancifully named B1202.

For it to be accepted, a newly bred variety must be demonstrably different from an existing cultivar and possess some advantage over existing ones, for instance, higher extractability. Not only must a new malting variety be capable of performing well in the maltings and brewery, it must also possess the necessary properties when growing in the field, such as high yield, disease resistance, a relatively short, stiff straw of uniform length, and early ripening.

To be accepted for malting, any barley will also need to satisfy other criteria. First of all, it should have a relatively low content of nitrogen, that is, protein. For a given size of grain, it is self-evident that the more protein packed into it, the less room there is for other components. In other words, the more protein, the less starch, and it is, of course, the starch the Brewer is primarily interested in, rather than a high protein content, which is needed in feed barley. Generally speaking, nitrogen levels will be lower in grain from barley grown on lighter soils. Maltsters place a specification on barley for its nitrogen content; in turn, this obliges the farmer to restrict the use of nitrogenous fertilizer. Accordingly, yields of malting barley tend to be lower than for crops grown for feed purposes. To compensate for this, a malting premium is paid for barley that meets the necessary criteria of uniformity in variety and low nitrogen.

Other specifications must be met, too. First and foremost, the barley must be living. If the embryo has been killed—which can occur all too easily, for example, if the barley has been badly dried—then it is incapable of producing the hormones that promote germination. Viability can be quickly checked by a staining test: living embryos cause a colorless tetrazolium dye to turn red.

Even if an embryo is alive, it may still not be capable of immediate germination. This is the so-called dormant state and it is quite normal, albeit an irritation to the maltster. Quite what controls dormancy in plant seeds is not known. It tends to vary from variety to variety, and it also depends on environmental factors. The further north barley is grown, the more it tends to display dormancy. Cool and wet conditions in the growing season promote dormancy. The phenomenon might be an irritation to the maltster, but it's important to the barley. If dormancy didn't exist, then the grain would germinate prematurely on the ear and not at the appropriate stage when it had left the parent plant and found its own bit of Mother Earth in which to sprout. For the same reason, the phenomenon is actually important to the maltster, too. In certain climatic conditions, such as high rainfall at certain stages in the growing season, grain can start to chit (sprout) on the ear. When such barley is harvested and dried, the heat kills the growing embryo and the malting process is jeopardized.

Dormant barley must be stored to allow it to recover from this condition. Various treatments have been recommended for the release of barley from dormancy, including warm storage (for example, 30°C) or, ironically, cold storage. It is certainly the case that a maltster might almost welcome dormancy if it was a condition he had total control over and could switch on or off at will in order to optimize barley purchasing and turnover.

A phenomenon related to dormancy is water sensitivity. All barleys, to a greater or lesser extent, display this trait, in which germination is inhibited by the presence of too much water. There are various plausible explanations for the effect, the most likely being the role of water in inhibiting the access of oxygen, which the embryo requires to support respiration. Recognition of the phenomenon about 40 years ago led directly to the introduction of interrupted steeping regimes in maltings. Previously barley had been steeped continuously in water. Once it was realized that this would suppress embryo activity by "swamping" it, procedures were introduced whereby barley is steeped for a shorter period of time, followed by a draining stage and then "air rest." Then more steep water is applied, followed by another air rest, and so on. The precise regime is optimized for each variety but seldom takes longer than 48 hours, whereas before the days of interrupted steeping the process took at least twice as long.

Brewers prefer barleys with larger corns, as they have a larger ratio of starch to peripheral tissue (e.g. husk, which can amount to as much as 10% of the weight of the grain).

The reader might suspect that one barley looks very much like another and it would be difficult to tell them apart. True, it is difficult, but an expert is able to inspect a handful of grain and pretty much identify the variety by studying things like color of the aleurone (some are white, others are blue), size of the corns, and length of the rachilla and the hairs on it (the rachilla is a remnant of the flowering stage in the development of the barley plant). Providing the sample is representative of the entire shipment, she will be able to tell whether she is looking at just one variety or a mixture. As barley varieties differ substantially in their performance, it is vital that they are malted separately, and the buyer would be entirely justified in rejecting a batch of barley on the basis of visual assessment alone. If further evidence is warranted, then this can be obtained by a protein fingerprint: the proteins of the grain are extracted and separated on gels, across which an electric current is passed. The proteins migrate to different extents on the gels before they are detected by staining. The patterns obtained are a characteristic of the variety (see fig. 4.2). More recently, just as in forensic science, the use of DNA fingerprinting has been suggested for barley: one might say it's to detect the crime of fraud in barley sales. A visual inspection, though, is generally sufficient—and it delivers, too, a verdict on whether the barley is free from infection and physical damage. It is rapid and can be performed when the barley is taken into the maltings.

Finally, different barleys possess different inherent flavors. Increasingly, barleys are being selected on the basis of an absence of undesirable flavor notes.

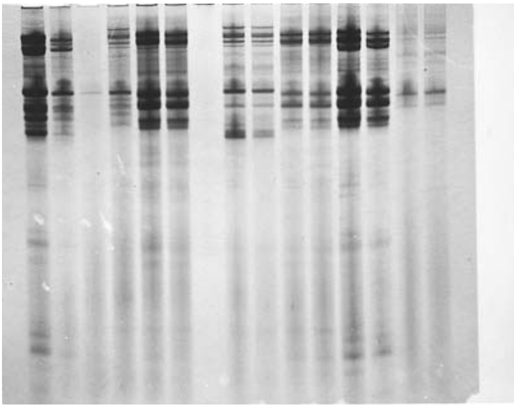


Figure 4.2 *A "protein fingerprint" of barley. Proteins are extracted from barley and separated on gels by electrophoresis (the protein mixture is applied to the top of the gel, and an electric current is passed through the gel; the various proteins move through the gel to different extents and are located by staining with a dye). Each of the bands shown in this photo represents a different protein, and each of the lanes has had extracts from different barleys applied to it.*

Commercial Malting Operations

There are four basic process stages in a modern malting operation: intake, drying, and storage of barley; steeping; germination; and kilning.

Intake, Drying, and Storage

Barleys can be classified into two categories, depending on when they are sown and harvested: Winter varieties are sown in the fall, whereas spring varieties are sown in spring and harvested a little later than the winter varieties. Generally speaking, the earlier in the year the seed is sown, the lower will be the protein content in the harvested grain (and the higher its yield) because starch accumulates all the way through the growing season.

Purchase of grain by the Maltster will be according to an agreed specification, which will include freedom from infection and infestation, its nitrogen content, grain size, viability, and moisture content. A typical specification for moisture in a two-row barley in the United Kingdom would be 16%. The farmer is paid proportionately less for batches of progressively higher water content, because the Maltster is obliged to dry them to an increased extent to prevent spoilage by insects and microorganisms. Most Maltsters don't favor the farmer taking responsibility for drying, for fear of destroying the embryo. In many parts of the world, including North America, drying is unnecessary, as the barley is harvested with a sufficiently low moisture content (12% or lower).

The grain will arrive at the maltings by road or rail; as the transport waits, it will be weighed, and a sample will be tested for the key parameters of viability, nitrogen content, and moisture. Expert evaluation will also provide a view on how clean the sample is in terms of weed content and on whether the grain "smells sweet." A few grains may be sliced in half lengthwise and their endosperms assessed as to whether they are mealy or steely. Remember: the Maltster prefers mealy endosperms. Once accepted, the barley will normally be cleaned, to remove everything from dust and weeds to dead rodents, and screened to remove small grain and dust, before passing into a silo, perhaps via a drying operation. Drying is seldom at temperatures greater than 55°C, with the grain not getting above 30°C due to the latent heat of evaporation (i.e., the heat energy consumed by water to enable it to evaporate; as the water "siphons" off the heat, the grain remains relatively cool). A continuous throughput of air is used, and drying may be continuous or in a batch operation.

Dry barley may be stored in various locations, ranging from steel- or concrete-framed sheds capable of holding up to 30,000 tons to steel bins holding no more than 750 tons. Whichever facility is used, it is essential that

A Selection of "Threats" to Barley

Diseases

Mildew: spread by wind from infected plants, infects grain

Take-all: spread by root contact, infects roots and base of stem

Eyespot: spread by splashing with rain, infects stem

Fusarium: spread by root contact, infects grain

"Rust": spread by wind, infects grain

Pests

Aphids: causes grain to be shriveled and discolored; carries the barley yellow dwarf virus

Leatherjackets: plants eaten away at ground level

Nematodes: attack roots

Rabbits: nibble seedlings

Birds: enjoy grain

the store is protected from the elements, yet it must also be ventilated, because barley, like other cereals, is a generous host (see "A Selection of 'Threats' to Barley"). The risk from different pests and diseases differs tremendously between sites and environments. Frequently no protective agents need to be employed, and they won't be unless it is absolutely necessary, but it is essential that pockets of infection by organisms such as *Penicillium* and *Aspergillus* don't occur and that the site is free from infestation by insects and vermin.

Barley is a hospitable vehicle for a selection of insects, including weevils, the saw-toothed grain beetle, and the quaintly named but no less undesirable confused flour beetle. Insecticides, approved for use on the basis of health and safety legislation, have an important role. Like anything else accumulating on the surface of barley, they are washed off during the steeping operation and so don't get into the malt used for brewing.

Although successive generations of barley varieties tend to have increased resistance to fungal infection, there is still dependence in certain growth regions on the application of systemic fungicides in the field to prevent the development of diseases such as mildew, eyespot, and take-all. These fungicides, by keeping the barley plant free from disease, help it to produce grain that is well filled and in really good condition for malting. Everybody benefits: the farmer, because he enjoys a high crop yield; the maltster, because she has good viable, healthy and fragrant barley to malt; the brewer, because the malt is uniformly of excellent quality and will "behave well" in the brewery, producing excellent beer in good yield—beer that is free from materials from any infectious agent on grain; and the consumer, because she will be purchasing a quality product with no defects that might be traced to the barley, for example, a flavor problem or gushing (see chapter 3).

Only pesticides and fungicides that have been rigorously assessed by legislative authorities and subsequently approved will be used. They will have received extensive screening on a health and safety basis, and it will have been demonstrated that they have no damaging effect on the barley, the process, or the product.

In the United States regulations on the use of pesticides apply at both the federal (Environmental Protection Agency) and state levels; and furthermore, bodies such as the Food and Drug Administration and the Occupational Safety and Health Administration have a say in what may and may not be done.

Steeping

The purpose of this stage is to increase the moisture content of the grain from 11–12% to 43–46% within two days. Kernels will not germinate if their moisture content is below 32%. A typical steeping regime will consist of an initial water stage for 6–16 hours, to raise the moisture content to 33–37%. An air rest for 12 to 24 hours follows, during which air is sucked downward through the grain bed to disturb films of moisture on the grain, expose the embryos to oxygen, and remove carbon dioxide produced by respiration, all of which is designed to prevent the embryo from being "suffocated." This will be followed by a second immersion of 10–20 hours, which will bring the moisture to the required level.

Water enters the grain through the micropyle, the small opening at the embryo end of the grain. The surface layers of the grain prevent access of water at any other point, unless these tissues have been deliberately damaged (see hereafter).

There are no hard-and-fast rules for steeping regimes: they are determined on a barley-by-barley basis by small-scale trials. It must be realized, too, that a barley changes in its properties over time. It increases in so-called vigor (the speed of growth essential for malting), which is reflected in enhanced capability for synthesizing enzymes and, therefore, rate of modification of the endosperm. A barley, then, will need to be processed differently in the maltings as the year goes on. In some locations barley is graded before steeping according to size, because different sizes of barley take up moisture at different rates.

Steeping vessels are normally fabricated from stainless steel and, most recently, are flat-bottomed ventilated vessels capable of holding as much as 250 tons of barley. The steep water (or “liquor,” as it is called in some parts of the world) is either from a well, when it is likely to have a relatively constant temperature, within the range 10–16°C, or from a city water supply, in which case there may be a need for temperature control facilities.

The aim of steeping is to achieve a homogeneous distribution of water across the entire bed of grain. The first steep (fig. 4.3) washes a large amount of material off the barley, including dust and leached tannins from the husk. It goes to drain without reuse and leads to a significant effluent charge.

A range of process aids has been used from time to time to promote the malting operation, and generally they have been introduced either in a steep or on transfer from steeping to germination. A few Maltsters still use potassium bromate to suppress the growth of rootlets within the embryo, for such growth is wasteful and can also cause matting, which leads to handling problems. Bromate also suppresses proteolysis. The use of bromate is not permitted in the United States.

Figure 4.3 *Steeping-in.*
Courtesy of Michael Lewis.

The Malting Fungus

The name *Gibberella fujikuroi* derives from the Japanese term "foolish seedling" and reflects the fact that infection of rice with this fungus led to "bolting" and very tall plants that tend to fall over. More than 80 gibberellins are known; the one most frequently employed in malting is GA_3.

More frequent worldwide is the use of gibberellic acid (GA), obtained from fermentations with the fungus *Gibberella fujikuroi* (see "The Malting Fungus"), to supplement the native gibberellins of the grain. Although some users of malt prohibit its use and it rarely (if ever) is used in the United States, GA can successfully accelerate the malting process. It tends to be sprayed on to grain at levels between 0.1 and 0.5 ppm as the grain passes from the last steep on its way to the germination vessel. Some maltsters couple the use of GA with a scarification process, whereby the end of the corn furthermost from the embryo is abraded. This enables water and GA to enter the distal end of the grain, triggering enzyme synthesis and modification in the region that is normally the last part to be degraded. Because these events are also being promoted "naturally" by the embryo, the resultant effect is called "two-way" modification. It is a way to accelerate the germination process and to deal with barleys that are more difficult to modify.

Germination

The aim of germination is to develop the enzymes that can hydrolyze the cell walls, the protein, and the starch of the barley and to ensure that these act to soften the endosperm by removing the cell walls and about half of the protein, while leaving the bulk of the starch behind.

Traditionally, steeped barley was spread out to a depth of up to 10 cm on the floors of long low buildings and germinated for periods of up to 10 days, with men using rakes either to thin out the grain ("the piece") or pile it up, depending on whether the batch needed its temperature lowered or raised: the aim was to maintain it at 13–16°C.

Very few floor maltings survive because of their labor intensity, although of course there are those who fervently believe that it's the only way to make decent malt. A pneumatic (mechanical) germination plant, with a range of designs, is now used. The earliest such germination vessels were rectangular, fabricated from brick or concrete, and known as Saladin boxes (fig. 4.4). They are still widely used and generally have a capacity of up to 250 tons. The floors of these vessels are made from perforated stainless steel to allow air to pass through the bed of grain. A mechanical turning system, such as a helical screw, is used to turn the grain and prevent matting of the rootlets (fig. 4.5). Newer germination vessels are circular, of steel or concrete, with capacities of as much as 500 tons, and they are microprocessor controlled. They may incorporate vertical turners located on radial rotating booms, but just as frequently it is the floor itself that rotates, against a fixed boom.

A modern malting plant is arranged in a tower format, with vessels vertically stacked, steeping tanks uppermost (fig. 4.6).

Germination in a pneumatic plant is generally at 16–20°C. In this process some 4% of the dry weight of the grain is consumed to support the growth of embryonic tissues, and much heat is produced. To dissipate this heat demands the use of large amounts of attemperated air, the oxygen of which is needed by the embryo for respiration; the carbon dioxide that is produced is flushed away by the air flow.

Take a walk through a malting plant with an experienced maltster, and you will see her grab a handful of germinating grain and spread it on the palm of one hand, glance at it, and then rub a few corns between the thumb and first finger. If the whole endosperm is readily squeezed out, and if the shoot initials (the acrospire) are about three-quarters of the length of the grain, then the "green malt" is ready for kilning.

Figure 4.4 *A germination "box." Photograph courtesy of Pauls Malt.*

Figure 4.5 *Germinated barley.*

Kilning

Kilning comprises the drying of malt to such a low level of moisture that it is stabilized, with germination arrested and enzymatic digestion halted. The enzymes of the malt, though, must not be destroyed: it is always important that the starch-degrading enzymes survive into malt, for the Brewer needs those to generate fermentable sugars in the mash. Often it is important that the cell wall and protein degrading enzymes survive, too, because they may not have completed their job in the maltings—and they may be needed to deal with proteins and polysaccharides present in unmalted adjuncts that the Brewer may use in mashing.

There is a great variety of kiln designs, but most modern kilns feature deep beds of malt. They may be rectangular, but they are more often circular in cross-section and are likely to be made from corrosion-resistant steel. They have a source of heat for warming incoming air and a fan to drive or pull the air through the bed, together with the necessary loading and stripping systems. The grain is supported on a wedge-wire floor, which permits air to pass through the bed, which is likely to be up to 1.2 meters deep. Figure 4.7 illustrates the loading of a kiln.

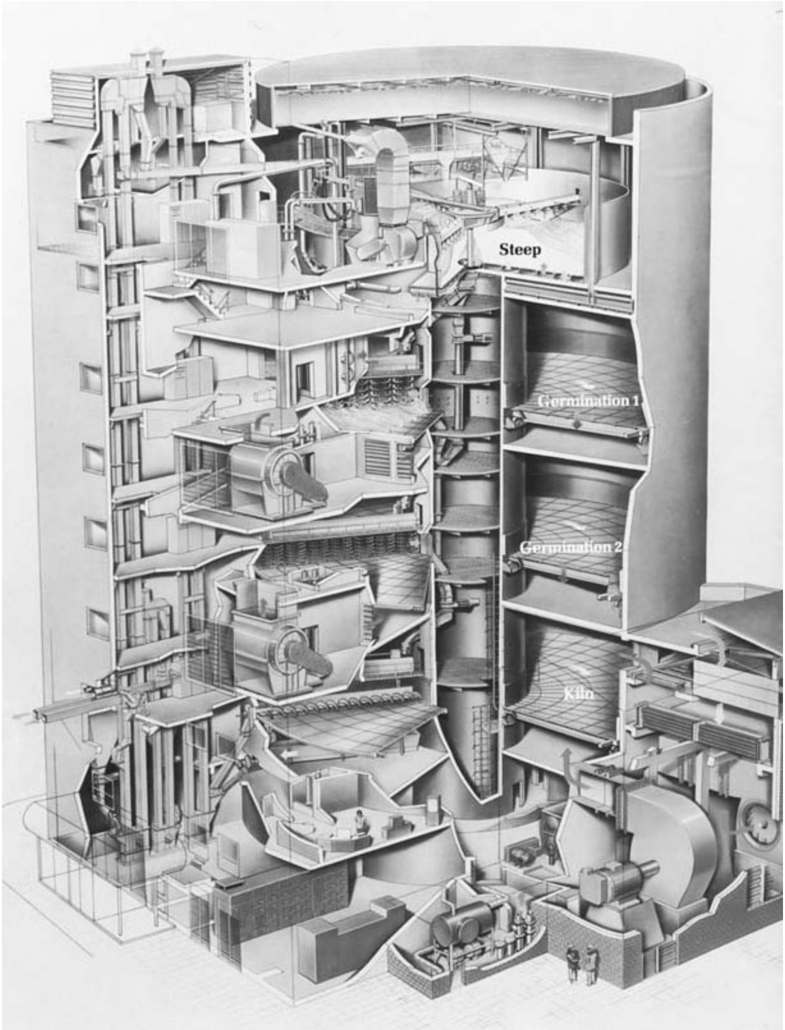


Figure 4.6. *A tower malting plant. Courtesy of Bass Maltings.*

Of course, kilning is an extremely energy-intensive operation, so modern kilns incorporate energy conservation systems such as glass tube air-to-air heat exchangers. Energy usage has been halved by such systems but can still amount to 2.85 gigajoules per ton of malt (see "Kilning of Malt Consumes a Lot of Energy").

Newer kilns also use "indirect firing": the products of fuel combustion don't pass through the grain bed but are sent to exhaust; the air is warmed using a heater battery that contains water as the conducting medium. Indi-

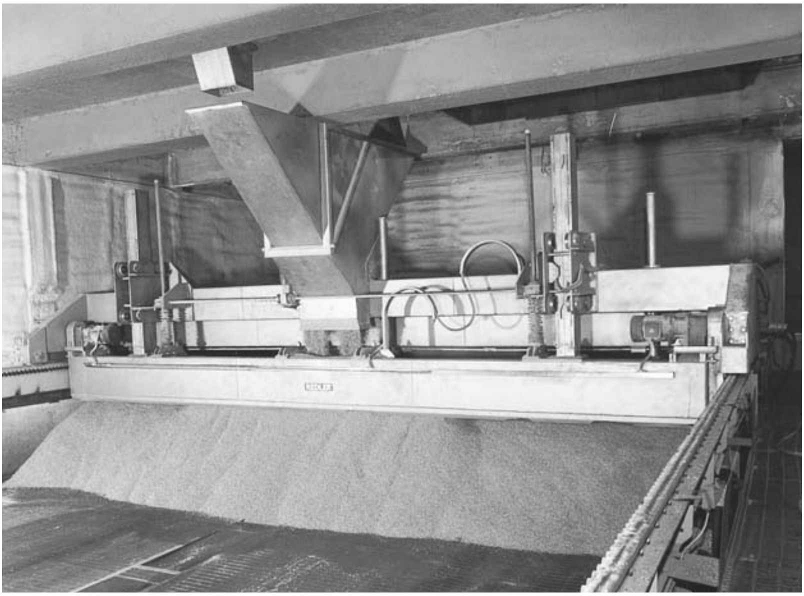


Figure 4.7 *Loading a malt kiln. Courtesy of Pauls Malt.*

rect firing arose because of concerns about the role of oxides of nitrogen present in kiln gases that might have promoted the formation of nitrosamines in malt. Nitrosamine levels have not been a problem in malt for many years.

Although the temperatures used in malt kilning are much higher, the physics of the drying of malt is very similar to that of the drying of barley, and both are somewhat complicated. There are, in fact, four phases to the drying process (fig. 4.8).

The first stage one consists of free drying. Air flows of up to 6000 m^3 min^{-1} t^{-1} are used, with the air entering the grain bed at 50–60°C (the so-called air-on temperature). At this stage the moisture content of the grain drops readily to approximately 23%. The remaining water is now more resistant to driving off and, indeed, is largely associated with grain components. Because water is not now being easily volatilized and is keeping the temperature of the bed down by latent heat of evaporation, the temperature of the air leaving the kiln ("air-off") starts to rise (the "break point"). The air-on temperature is increased, and, at this intermediate stage, moisture in the bed is lowered to 12%. All of the water is now bound, and the temperature is raised again and the fan speed reduced until the water level in the bed is approximately 6%. Finally comes the "curing" phase, which is designed to lower the moisture to final specification, which is typically 4% or lower. At this stage the air-on temperature may be anything between 75 and 110°C, depending on the type of malt required. Lower temperatures will give malts

Kilning of Malt Consumes a Lot of Energy

James Prescott Joule (1818–1889) might have emulated his dad and become a brewer. Instead he was fascinated by chemistry (he studied in Manchester, England), but he soon turned his attention to physics, performing his experiments at home because of severe invalidity. In particular he was interested in the amount of heat that equated to mechanical energy, and in his most famous investigation he studied the extent to which water was warmed by vigorously spinning paddles in it. Joule found that the work done by a 1-pound weight (0.45 kg) falling through a distance of 9 inches (23 cm) raises the temperature of 1 gram of water by 1°C. This quantity of work has henceforth been referred to as a joule, which is now the standard unit of heat.

"Giga" means one thousand million; the kilning of each ton of malt burns up nearly three gigajoules. That sounds like a lot, and it is—the equivalent of 400 men working solidly and energetically for eight hours.

of lighter color and will tend to be employed in the production of malts destined for lager-style beers. Higher temperatures, apart from giving darker malts, also lead to a wholly different flavor spectrum. Lager malts give beers that are relatively rich in sulfur compounds, including dimethyl sulfide. Ale malts have more roast, nutty characters. For both lager and ale malts, kilning is sufficient to eliminate the unpleasant raw, grassy, and beany characters associated with green malt.

When kilning is complete, the heat is switched off, and the grain allowed to cool before it is stripped from the kiln in a stream of air at ambient temperatures. On its way to steel or concrete hopper-bottomed storage silos, the malt is "dressed," which involves mechanical removal of dried rootlets (referred to as "culms," which go to animal feed), aspiration of dust, sifting out of loose husk and incomplete kernels, and the elimination of any large contaminants.

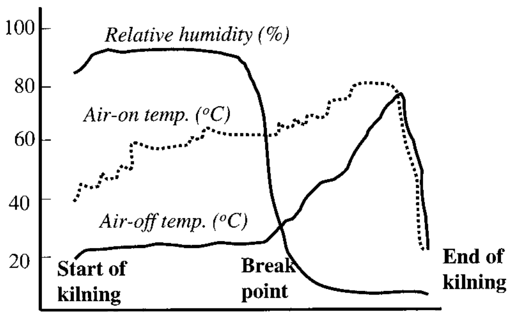


Figure 4.8 *Changes in moisture and malt bed temperature during kilning.*

Specialty Malts

Some malts are produced not for their enzyme content but rather for use by the Brewer in relatively small quantities as a source of extra color and distinct types of flavor. They may also be useful sources of natural antioxidant materials. There is much interest in these products for the opportunities they present for brewing different styles of beer. Table 4.2 describes some of these malts, which are produced in small drum kilns equipped with water sprays, for obvious reasons. Those specialty malts that are produced with the least extra heating (e.g. cara pils and crystal malt) can be used to introduce relatively sweet, toffeelike characters. Those produced with intense heating (e.g., black malt) deliver potent burnt and smoky notes.

What the Brewer Looks for in a Malt

As the years have passed, and the links have progressively been established between malt composition, the behavior of a malt in the brewery, and the quality of the finished beer, more and more demands have been placed on the Maltster by the Brewer. There has been a tendency, still prevalent among the traditionalists, for the Brewer to blame the poor old Maltster whenever things go wrong. The trend, too, has been for the Brewer to place more and more specifications on the malt, in many cases rather unfairly, because the demands are often contradictory. For instance, a Brewer may insist on the malt being well modified, with very little cell wall material surviving, while also demanding that it contains very little DMS precursor. However, prolonged germination periods, which enable better cell wall breakdown, go

Table 4.2
Colored Malts

Type	*Color (°EBC)*	*Production regime*
Cara Pils	15–30	The surface moisture is dried off at 50°C , before stewing over 40 minutes with the temperature increased to 100°C, followed by curing at 100–120°C for less than 1 hour
Crystal	75–300	As for Cara Pils, but first curing is at 135°C for less than 2 hours
Chocolate	500–1200	Lager malt is roasted, by taking temperature from 75 to 150°C over 1 hour, before allowing temperature to rise to 220°C
Black	1200–1400	Similar to chocolate malt, but the roasting is even more intense

Source: Based on C. W. Bamforth and A. H. P. Barclay, *Malting Technology and the Uses of Malt,* edited by Alexander W. MacGregor and Rattan S. Bhatty (St. Paul, Minn.: American Association of Cereal Chemists, 1993), pp. 297–354.

hand in hand with high DMS precursor. The Maltster could suppress DMS precursor development by using bromate, but as often as not the Brewer will stipulate that the malt should be additive free. Understandably, all this can leave the Maltster in a quandary. It may be that he will need to resort to the blending of different batches in order to "hit" specification.

Brewers apply a wide range of specifications to malt. Many Brewers, applying quality assurance principles, will look to the Maltster to provide documentation with the malt shipment that details all the required analyses on a batch of malt, certifying that the malt meets the required tolerances. The Brewer will spot-check occasional batches. Heaven protect the transgressing Maltster! From time to time, too, the Brewer will audit the Maltster (as, indeed, it will audit most of its raw material suppliers). I don't believe that there is a Brewer today who applies the sliced bread test for auditing maltings hygiene: time was when the Brewer would visit the maltings, wipe the inside of a vessel with a piece of bread, and invite the Maltster to eat it for breakfast. Crude certainly, but a powerful incentive for the Maltster to keep the plant spotless!

Thankfully, most of the analytical methodology applied to assess malt quality is somewhat more sophisticated than this.

The most important parameter is the so-called hot water extract, which is a measure of the total material that can be solubilized from the malt in a mashing operation. As such, it reflects the extent to which the endosperm has become solubilized during germination of barley and also that insoluble fraction from malt that is released by enzymes during mashing. The higher the value, then potentially the more alcohol will be derived by the Brewer per unit of malt and the more valuable the malt, providing that other relevant specifications are met. The hot water extract is typically measured on 50g of malt, which is milled, mixed with water at 65°C, and stirred for an hour in a beaker. The liquid portion is then filtered off from the spent grains and its specific gravity measured: the higher the specific gravity, the more dissolved material.

Brewers realize, however, that while material may be readily extracted from a batch of malt in a small-scale test, this may not be the case in a full-scale brewery operation. There are various reasons for this, but the most important one is that a batch of malt with a large proportion of relatively under-modified kernels will give large particles after roller-milling, and these particles will not be extracted so readily. Brewers may, therefore, insist on some measure of modification being applied to the malt. The most common of these involves the fluorochrome calcofluor. A typical procedure is for 50 grains to be embedded in plastic and, literally, partly ground down, using the sort of electric sander that you might use in your home decorating. This exposes the starchy endosperm, which can be examined longitudinally. Calcofluor, a material that was originally developed for use in domestic washing powders, is added. Calcofluor can bind on to the cellulose fibers in shirts and emit a strong fluorescence, rendering the shirts "whiter than white." Of more interest to the Brewer (at least for testing the malt) is the fact that the Calcofluor also latches on to the β-glucan in the endosperm cell walls of barley. Inspection of a Calcofluor-stained sanded malt sample, therefore, highlights whether the cell walls in the malt have or have not been efficiently removed during germination and with what consistency between corns. High levels of fluorescence indicate high levels of residual wall and associated poor extractability of the malt.

The small-scale mash mentioned earlier for the measurement of hot water extract is also analyzed for the level of protein it contains, higher levels indicating more extensive modification. Actually, it is total nitrogen that is measured, not protein. For many years the nitrogen was measured using a method developed by Johan Kjeldahl (fig. 4.9) in 1883 at the Carlsberg Laboratories, a standard procedure for measuring bound nitrogen which has long been applied far beyond malting and brewing (see "Johan Kjeldahl [1849–1900]"). More recently a safer method, devised by Jean Baptiste André Dumas, has superseded Kjeldahl's procedure.

More useful to the Brewer than the measure of "total soluble nitrogen" is that of "free amino nitrogen" (FAN): the level of amino acids in the wort. Apart from influencing whether wort will or will not be fermented by yeast,

Figure 4.9. *Johan Kjeldahl. Reproduced courtesy of Carlsberg, from* The Carlsberg Laboratory 1876–1976.

the FAN levels also influence the extent to which yeast produces flavor compounds, such as esters: therefore it affects beer flavor. Furthermore, if the FAN level is too high, then there will be more than enough for the yeast to use during fermentation. Any FAN left over in beer is a hazard, insofar as could make a tasty meal for spoilage organisms.

The wort from the small-scale mash is also used to assess color, generally by measuring the amount of light absorbed at 430 nm, and wort viscosity is also taken as an indicator of potential wort separation and beer filtration problems. High-viscosity liquids flow more slowly.

The level of moisture in malt is measured by oven drying of the malt itself. The level of various enzymes in the malt may be measured, too. If the hot water extract, viscosity, FAN, and modification form part of the specification, it should seldom be necessary to quote specific enzyme levels, as these parameters will only be within specification if the appropriate starch-, cell-wall, and protein-degrading enzymes are present. A Brewer may, however, require a measure of the major cell-wall degrading enzyme, β-glucanase, to confirm that kilning has not been excessive, especially if the malt is to be used as the enzyme source for dealing with adjuncts.

Johan Kjeldahl (1849–1900)

Few names in the world of analytical chemistry are better recognized than that of Kjeldahl. His method for measuring the level of nitrogen contained in all types of sample, notably foodstuffs, became the accepted standard from the time it was first developed in 1883. Nitrogen in this context is not gaseous nitrogen, which occupies some 79% of the earth's atmosphere, but rather the nitrogen that is part of chemical compounds. In particular, nitrogen is a key component of two types of substance that form the architecture and working elements of living matter, namely the proteins and the nucleic acids. Indeed when Maltsters and Brewers refer to the nitrogen content of a barley, malt, or wort they are really using this as a measure of the amount of protein in that sample.

Working at the Carlsberg Laboratories, which he joined on May 1, 1875, Kjeldahl developed a procedure involving the hydrolysis of proteins to release ammonia, which could be readily measured colorimetrically. The more ammonia was released, the more protein was present. A standard relationship was demonstrated that showed that the amount of protein equated the amount of nitrogen multiplied by a factor of 6.25.

Kjeldahl did research on many other topics, but his name will forever be associated with protein measurement. Tragically, Kjeldahl suffered from severe depression and exhaustion, which are said to have interfered with his experimental work, yet he was also understood to be the life and soul of many a party.

Brewers will specify that the nitrosamine content must be below a certain level (typically less than 1 ppb). As I have mentioned, it is very likely that a Brewer will place a specification for DMS precursor in lager malts, either at a low level, if it feels that its lager suffers from the presence of DMS, or at a higher level, if it believes that DMS in reasonable quantities makes a positive contribution to lager flavor.

DMS, as we have seen, is just one of the flavors of beer that can originate in malt. Rather more flavor is contributed by yeast, as we shall see in chapter 7. However, when most people think of beer flavor, they automatically summon up a picture of hops, my topic in the next chapter.

5

The Wicked and Pernicious Weed

Hops

When many people consider beer they automatically think of hops. Lots of people are misguided and believe that hops alone are the basic raw materials for making beer, with all of the alcohol and flavor flowing from them. Of course it is the starch in malted barley and adjuncts that serves as the origin of the fermentation feedstock that yeast uses to make alcohol. Hops are, indeed, simply a flavoring material, albeit one that has other key impacts on beer and brewing. However, as we shall see (and as shown in chapter 3), the chemistry of hops and hopping is anything but "simple."

The History of Hops

Hops were cultivated in Babylon as far back as A.D. 200, but not until 1079 do we find mention of the use of hops in making beer. Indeed beers at that time were flavored with all manner of herbs, including rosemary, yarrow, coriander, and bog myrtle, which were added in mixtures known as gruit. There has even been reference to the use in beer of caraway, pepper, pine roots, spruce, potato leaves, and tobacco.

As I mentioned in chapter 1, it was in the thirteenth century that the hop started to threaten gruit as a flavoring for beers in Germany. "Threaten" is a word I use advisedly, for growers in all countries of the hitherto "traditional" flavorings fought vigorously against the introduction of hops. The plant was banned from use in the brewing of beer in Norwich, England, in

1471, and in 1519 hops were condemned by the English as being a "wicked and pernicious weed" (see Corran in further reading section).

Medieval adherents of ale (which was a term then restricted to unhopped beer) would also have rebelled, if not necessarily the Brewers. The ales drinkers were used to were strong and sweet—and deliberately so, for high concentrations of sugar and alcohol suppress the growth of the microorganisms that can ruin the product. Hops, though, have strong antiseptic properties. Using them in beer enabled Brewers to "thin out" the drink and make it weaker. The first hopped beer was seen in England in 1400, when it was imported from Holland through Winchelsea.

Hops started to be grown in southeast England in 1524, a hundred years before they were first cultivated in North America. Just as the Yakima Valley in Washington state is famed for its hops, so too is Kent, the "garden of England."

The tirade against hops was relentless. Andrew Boorde wrote in 1542:

> Bere is made of malte, hoppes, and water; it is the naturall drynke for a Dutcheman, and nowe of lete days it is much used in England to the detryment of many Englysshe people; specially it kylleth them which be troubled with the colyke; and the stone and the strangulion; for the drynke is a colde drynke, yet it doth make a man fat, and doth inflate the bely, as it doth appere by the Dutche men's faces and belyes. If the bere be well served and be fyned and not new, it doth qualify heat of the liver.[1]

Not a particularly supportive reference (and humble felicitations to my good friends at Heineken). Happily, a somewhat different view of hops and their contribution to beer quality now exists, and these days very little malt-based beer is devoid of hops. However, the manner by which the unique bitterness and aroma of the plant is introduced into the beverage is often very different from that of six centuries ago.

A Solitary Outlet

The hop is remarkable among agricultural crops in that essentially its sole outlet is for brewing, apart from a somewhat limited market for its oils in aromatherapy and its whole cones in hop pillows: it is variously said that if you sleep on such a pillow you will not only sleep well but also dream about your true love. The Romans used hops as a spring vegetable, though quite how popular it was when used in that way is lost in the fogs of time.

Although hopping accounts for much less than 1% of the price of a pint of beer, it has a disproportionate effect on product quality, accordingly, much attention has been lavished on the hop and its chemistry.

Table 5.1
Production of Hops (1998)

Country	*Hop production (thousand hectares)*
Germany	21
United States	18
China	7
Czech Republic and Slovakia	6
Poland	3
Slovenia	3
England	2
Russia and Ukraine	2
Australia	1
France	1
Spain	1

Note: Values are rounded to nearest whole number.

Hops are grown in all temperate regions of the world (table 5.1). More than 100,000 tons are grown each year, approximately one-third of those in Germany, with the United States being the next largest producer, with the bulk of cultivation being in three states: Washington, Oregon, and Idaho. Hops are grown in the Southern Hemisphere as well as the North, with a significant crop in Australia, notably in Tasmania.

There are two separate species of hops: *Humulus lupulus* and *Humulus japonicus*. The Romans called hops *Lupus salictarius; Lupus* means "wolf," and the hop was likened to a wolf among sheep because it grew wild amid the willow. *H. japonicus* contains no resin and is merely ornamental. Hops for brewing are within *H. lupulus,* which is rich in resins and oils, the former being the source of bitterness, the latter the source of aroma.

The hop genus (*Humulus*) is within the family *Cannabinaceae,* and *Cannabis sativa,* Indian hemp, better known as marijuana or hashish, is a close relative of the hop. A key point of distinction is in their respective resins (fig. 5.1): those from hops make beer bitter; those from marijuana have hallucinogenic effects, or so I am led to believe. Whether anyone has tried to smoke hops I know not.

Cultivation

Hops are hardy climbing herbaceous perennial plants. They are grown in yards using characteristic string frameworks to support them (figs. 5.2 and 5.3). Their rootstock remains in the ground year after year and is spaced in

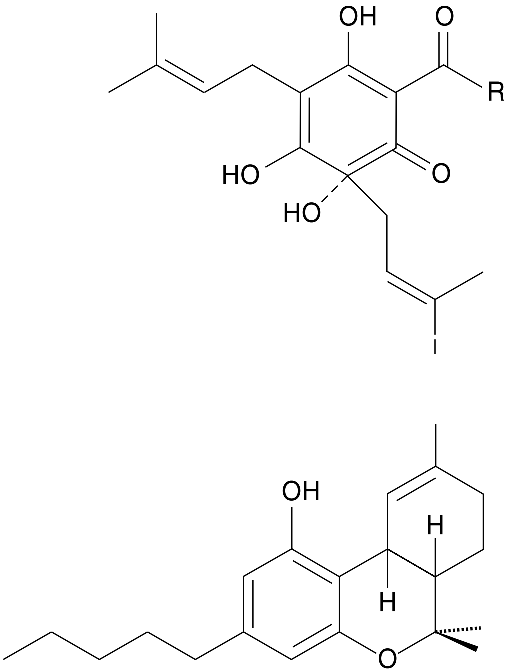


Figure 5.1 *The resins from hops (top) and cannabis (bottom).*

an appropriate fashion for effective horticultural procedures (for example, spraying from tractors passing between rows). In recent years, so-called dwarf varieties have been bred that retain the bittering and aroma potential of "traditional" hops but grow to a shorter height (6–8 feet as opposed to twice as tall). As a result they are much easier to harvest, and there is less waste of pesticide during spraying. Dwarf hop gardens are also much cheaper to establish, at a typical cost of $2,500, which is a third lower than for nondwarf varieties.

Hops are susceptible to a wide range of diseases and pests (see "Diseases and Pests in Hops"). The most serious diseases are *Verticillium* wilt, mildew, and mold, with the damson-hop aphid an especially unwelcome visitor. Varieties differ in their susceptibility to infestation and have been progressively selected on this basis. Nonetheless, it is frequently necessary to apply pesticides, which are always stringently evaluated for their influence on hop quality, for any effect they may have on the brewing process, and, of course, for their safety. A Brewer will not use hops or hop preparations (or, indeed, any other raw material) unless absolutely convinced that they will be entirely hazard free for process, product, and consumer.

Some hop-growing regions present more of a problem in terms of diseases and pests than others. For instance, whereas mildew has regularly been of concern in Europe, it has virtually been unheard-of as a problem in the United States since it was first observed there in 1909 in hop gardens on

Figure 5.2 *Hops growing in Yakima, Washington. Courtesy of John I. Haas, Inc.*

the East Coast, a finding that precipitated the shift of the hop-growing business to the opposite coast. Unheard-of, that is, until 1997, when in excess of 50% of the hop crop in the Yakima Valley succumbed to powdery mildew.

The components of the hop required by the Brewer—the resins and the oils—are located in the cones of the female plants (fig. 5.4). More exactly, they are found in the lupulin glands, which are alongside the seeds at the base of the bracteoles (fig. 5.5).

Figure 5.3 *Harvesting hops in Yakima. Courtesy of John I. Haas, Inc.*

Diseases and Pests in Hops

Downy mildew is caused by a fungus, *Pseudoperonospora humuli.* The disease is rapidly transmitted between parts of plants and separate plants. Infection may prevent the development of cones, and where cones do develop, yield of the α-acid precursors of bitter compounds is reduced. Infected stock must be burnt, and the grower must realize that mycelia may persist in rootstock and demand attention in subsequent years.

Hop mould (powdery mildew) is caused by the fungus *Sphaerotheca macularis;* it reveals itself as red patches on leaves and cones. One effective treatment involves spraying with sulfur.

The third fungal disease of hops, wilt, is due to *Verticillium albo-atrum.* Again, it can spread rapidly and demands urgent attention if it is to be contained. For instance, in the United Kingdom, it is a legal requirement that discovery of wilt be reported immediately. Infection demands the burning of plants and infected rootstock. Small wonder that hop growers are stringent in their precautions when allowing outsiders to visit their gardens.

The most significant pest that infects hops is the hop-fly, more commonly referred to as the damson-hop aphid because its eggs spend the winter in the bark of the damson (or sloe or plum), with the hatched flies subsequently migrating to the hop.

Internationally there are differences in preference for seeded as opposed to unseeded hops. In the United Kingdom, male plants are included alongside female plants, leading to fertilization and seed levels of up to 25%. Hops are perennial, however, and can be propagated from cuttings, so, unfortunately for the male of the species, his services can be readily dispensed with. Indeed, in the rest of Europe and the United States (with some exceptions in Oregon), there is no planting of male hops, and the hops supplied for brewing are seedless. On a weight-by-weight basis the content of resin and oil is greater in seedless hops, but horticultural yield is lower. It is believed by some that seedless hops make for easier downstream processing of beer.

A typical grower's year in the hop-growing district of Yakima, Washington, will commence in March with some shallow plowing to lower the weed count and to mulch into the ground residual leaves and vines from the previous crop, as well as some fertilizer. In the following month, the wirework will be established on wooden poles 3 m high and spaced 2 m apart; new shoots from the rootstock are then trained onto the strings. In June, plowing is undertaken to control weeds, and spraying is done in July and August to control pests. Harvest commences in mid-August and lasts for a month.

Hops are harvested within a similar time span in the Kent and Hereford-and-Worcester hop gardens of England, but through the month of September. Traditionally this was a very labor-intensive operation, demanding

Figure 5.4 *Hop cones. Courtesy of John I. Haas, Inc.*

short-term labor bussed in from the city; but now machine picking is universally employed.

Drying of hops is according to similar principles to those for barley and malt (see chapter 4) and was traditionally performed in oast houses (fig. 5.6). Nowadays these charming buildings are far more likely to be employed as

Figure 5.5 *Inside a hop cone. The central axis, like a stem, is called the "strig"; attached to it are the bracteoles. The paler regions where the bracteoles meet the strig are the lupulin glands, where the resins are located. Courtesy of John I. Haas, Inc.*

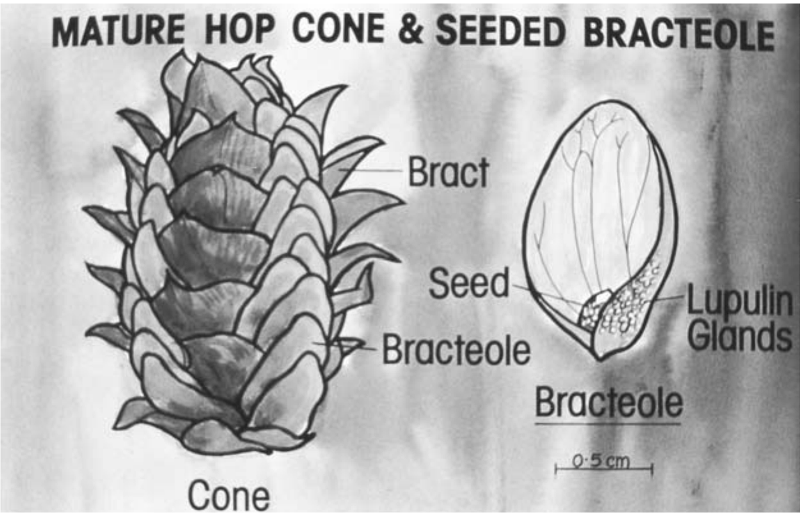


Figure 5.6 *An oast house. Courtesy of Tim Bailey.*

homes than for drying hops, which these days is done in modern kilns. Using temperature regimes of between 55 and 65°C, the moisture content is reduced from 75% to 9%. Traditionally in the United Kingdom hops are delivered to the Brewer compressed in jute (now polypropylene) sacks about 7 feet deep. These are called "pockets"; each holds approximately 75 kg (or 1.5 zentners—the zentner [50 kg] is the traditional unit for quantifying the weight of hops). In the United States, hops are packed into bales measuring 20 by 30 by 57 inches and weighing 200 pounds (91 kg or 1.8 zentners). The hops must be stored cold and in an airtight condition, to counter the degradation of the bitter principles and the attendant development of nasty cheesy characteristics. As I will show, though, the use of hop cones without some form of modification is increasingly rare these days.

Hop Analysis

As with all raw materials used in the brewing process, specifications are applied to hops that must be met if a transaction is to be conducted between the hop merchant and the Brewer. It is fair to say that the analysis of hops remains somewhat more primitive than that of other brewery ingredients. Many of the assessment criteria for hop quality depend on noninstrumental judgment by experts. First the sample of hops will be inspected visually for signs of deterioration, infestation, or weathering. Then a sample will be rubbed between the palms of the hands before sniffing the contents: the assessor is looking for any smells associated with deterioration and, just as important, is determining whether the "nose" is consistent with what is expected from the variety in question. The buyer is not looking for a character that will manifest itself in the finished beer, for the aroma of hops and that of hoppiness in beer seldom bear a simple relationship. Rather she is looking for certain varietal characteristics in the aroma to confirm that the hop is what it is purported to be.

The prime quantitative parameter on which hop transactions are made in the United Kingdom is the lead conductance value. Lead acetate is added to an extract of hop resins in methanol, and the conductivity of the mixture is measured. The lead ions react with the resin α-acids (which are the precursors of the bitter compounds). Once all of the lead has complexed and surplus lead is present, the conductivity starts to change. The more lead acetate needs to be added before the conductivity changes, the more α-acid is present. In the United States α-acids are measured spectrophotometrically: as the extent to which an extract made from the hops absorbs ultraviolet light in proportion to the amount of resins present.

Types of Hops

There is an increasing tendency to classify hops into two categories: aroma hops and bittering hops. In reality they are merely variations on a theme. All hops are capable of providing both bitterness and aroma. Some hops, however, such as the Czech variety Saaz, have a relatively high ratio of oil to resin, and the character of the oil component is particularly prized. Such varieties command higher prices and are known as aroma varieties. They will seldom be used as the sole source of bitterness and aroma in a beer: a cheaper, higher α-acid hop (a bittering variety) will be used to provide the bulk of the bitterness, with the prized aroma variety added late in the boil for the contribution of its own unique blend of oils. Those Brewers requiring hops solely as a source of bitterness may well opt for a cheaper variety, ensuring its use early in the kettle boil so that the provision of bitterness is maximized and unwanted aroma is driven off.

In just the same way that there are many varieties of malting barley and fierce loyalty is shown by Brewers to one or a very few of these varieties, the selection of hops is a serious concern for the Brewer. In some countries one variety prevails, as is the case in Australia, where Pride of Ringwood has held center stage for many years. This situation can be compared with that in the United States, where one bittering variety, Cluster, which has been in use since 1800, is joined these days by the likes of Eroica, Galena, and Nugget, whereas aroma varieties like Mount Hood have only emerged in the last 10 years. The U.S. market is an interesting mix of modern and traditional, for prized aroma varieties like the English Fuggles and German Tettnang have been in use for over a century. Some of the varieties are classified as "dual purpose," being considered useful both for bitterness and high quality aroma potential. These include Chinook and the German variety Perle. Some consider Cluster to be in this category.

The history of Fuggles is a good example of the pressures that drive the hop market. It was introduced in 1875 in Kent and half a century ago accounted for 75% of the English hop crop. Its problem is an acute susceptibility to *Verticillium* wilt. Breeding programs have delivered just one variant of Fuggles (Progress) that shows a sufficiently improved resistance. Accordingly, programs have focused on seeking in other varieties the necessary blend of quality and disease-resistance characteristics. So far, no single variety displays a comprehensive resistance to all diseases while simultaneously displaying high bitterness potential and good aroma.

The most famed hop-growing region is the Hallertau, north of Munich, where a hop garden was first reported in the year 736. The western part of the Czech Republic, a region known as Bohemia, is also celebrated for its hops. "Good" King Wenceslas, indeed, introduced the death penalty for anyone who exported hop cuttings from Bohemia!

Hop Chemistry

Hops contain a range of chemical species, including cellulose and lignin as structural components, proteins, lipids and waxes, and tannins. We need consider only two of the constituents of hops: the resins and the essential oils.

Resins

There are several components in the resin portion of the hop. The chemistry is rather complex, but most Brewers consider only one type of component significant: the α-acids. These molecules, also known as the humulones, can account for as little as 2% of the dry weight of the hop or as much as 15%. Clearly a "high-alpha" variety, such as Target in the United Kingdom or Nugget in the United States, is a richer source of bitterness. Less of it will need to be used to impart a given bitterness level to beer, but of course there will be a proportionately lower contribution of the essential oils, thus less aroma potential. Conversely, a low-alpha hop, such as Fuggles or Tettnang, needs to be used in larger proportions to afford a desired bitterness, which leads to greater potential aroma delivery. The Brewer is then at risk of introducing other undesirable materials, such as the tannins that promote haziness in beer.

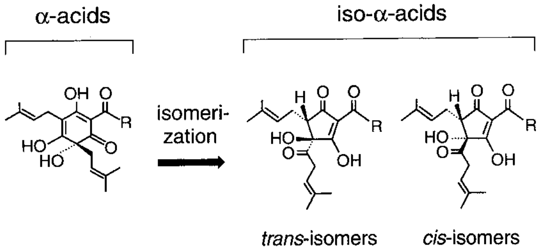
There are three variants of the α-acids (cohumulone, humulone, and adhumulone); they differ very slightly in the structure of the so-called side-chain labeled "R," which attaches to the ring (see fig. 5.1, top right). Received wisdom says that "better" hops have a relatively low proportion of cohumulone.

When wort is boiled in the kettle (see chapter 6), the α-acids are rearranged to form iso-α-acids in a process referred to as "isomerization" (fig. 5.7). The products are much more soluble than the humulones and are bitterer. At the end of boiling, any unisomerized α-acid is lost with the spent hop material, and the iso-α-acids remain. The process is not particularly efficient, with perhaps no more than 50% of the α-acids being converted in the boil and less than 25% of the original bittering potential surviving into the beer. Each iso-α-acid exists in two forms, *cis* and *trans,* which differ in the orientation of the side chains (fig. 5.7). The six iso-α-acids differ in the quality and intensity of their bitterness (see chapter 3).

Essential Oils

The oil component of hops ranges from just 0.03% to 3% of the weight of a hop. Seedless hops tend to contain more essential oil. The oils are produced in the hop late in ripening, after the majority of the resin has been laid down, which highlights the need for harvesting of the hops at the appropriate time.

The oil is a complex mixture of at least 300 compounds. Nobody can yet claim to have established a clear relationship between the chemical composition of the essential oils and the unique aroma characteristics they deliver. The science is enormously complicated, as a glance at the sorts of compound that contribute to hop aroma shows (fig. 5.8). It is most likely that "late hop character" (i.e., the aroma associated with lagers from mainland



R = $CH_2CH(CH_3)_2$	humulone	isohumulone
R = $CH(CH_3)_2$	cohumulone	isocohumulone
R = $CH(CH_3)\,CH_2CH_3$	adhumulone	isoadhumulone

Figure 5.7 *Isomerization.*

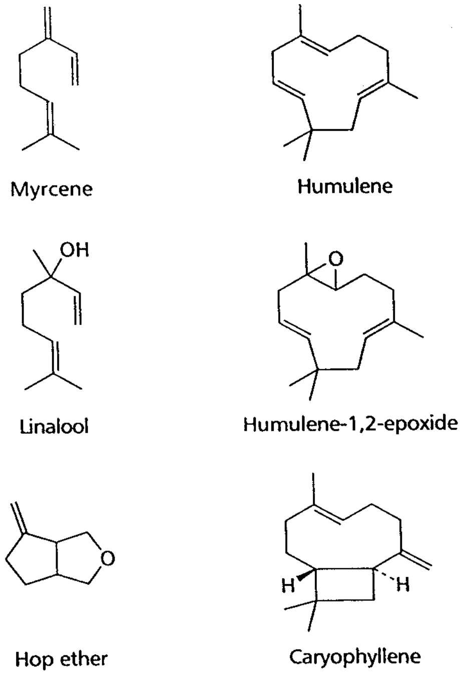


Figure 5.8 Some essential oils from hops.

Europe that is introduced by adding a proportion of the hops late in the boil) is due to the synergistic action of several oil components, perhaps modified by the action of yeast in the ensuing fermentation. "Dry hop character" (a feature associated with traditional English cask ales, afforded by adding a handful of whole hop cones to the vessel) is no less complicated. Generally it would be held that myrcene, the major hydrocarbon component, is an undesirable feature of the oil, whereas compounds such as linalool and geraniol, which are present in far lower concentrations, offer attractive aroma notes. To a greater or lesser extent the individual essential oil components are lost from wort during boiling. The delivery of a given hop character, then, depends on the skill of the brewster in adding the hops at exactly the right time to ensure survival of the right mix of oils that imparts a given character to the product. No instrumental method is yet available to assist in this process.

Hop Preparations

The use of whole cone hops is comparatively rare nowadays, although the world's biggest Brewer, Anheuser-Busch, steadfastly maintains this tradition. The most common procedure for hopping is to add hops that have been hammer-milled and then compressed into pellets (fig. 5.9). In this form they are more stable and more efficiently utilized and do not present the Brewer with the problem of separating out the vegetative parts of the hop plant.

Nevertheless, because of the inefficient utilization of the α-acids during wort boiling, even from pellets, and as a result of vagaries in the introduction of defined hoppy aromas into beers, a wide selection of hop preparations have reached the marketplace. We can actually trace proposals for making hop extracts back to 1820, when lupulin glands were extracted with lime, alcohol, and ether! These days, extracts are mostly based on the prior extraction of hops with liquid or supercritical carbon dioxide.

It was first shown over 30 years ago that the resins and oils of hops could be extracted using as a solvent carbon dioxide that has been liquefied at high pressure and low temperature. The resultant extracts can be fractionated into resin- and hop oil–rich fractions, with the resin portion being available as a source of bitterness for addition in place of whole hops or pellets to the kettle and the oil part providing an opportunity for controlled addition of hop character, either by dosing late in the boil for a late hop character or into the finished beer for a dry hop note.

It is possible to carry out the isomerization of the α-acids in the liquid CO_2 extracts by chemical means or by the use of light. Therefore, it is possible, using the resultant "pre-isomerized extracts," to add bitterness directly to the finished beer, which makes for far better utilization of the bitter compounds, because the extent of isomerization of α-acids is greater and because bitter substances are no longer lost by sticking onto yeast cells. A siz-

Figure 5.9 *Hop pellets. Courtesy of John I. Haas, Inc.*

able amount of beer is brewed worldwide where all of the bitterness is introduced in this way.

Recent years have been marked by an enormous increase in the use of such preisomerized extracts after they have been modified by a process known as reduction. One of the side-chains on the iso-α-acids is susceptible to cleavage by light; it then reacts with traces of sulfidic materials in beer to produce MBT, which imparts an intensely unpleasant skunky character to beer. If the side-chain is reduced, it no longer produces MBT. For this reason, beers that are destined for packaging in green or clear glass bottles are often produced using these modified bitterness preparations, which have the added advantage of possessing increased foam-stabilizing and antimicrobial properties.

Late hop aroma can be introduced through the use of extracts, too. It has been shown that the essential oils can be split into two fractions, one of which is spicy and the other floral. By adding them to bright beer in different proportions, it is possible to impart different late hop characters, again offering tremendous opportunities for new product development. Here is a mechanism for the Brewer to introduce under controlled conditions a range of flavor characteristics to beer and potentially to create a selection of different products by downstream adjustment of a single base beer.

Clearly, the extraction of hops to make products such as pre-isomerized extracts, reduced iso-α-acids, and late hop essences has introduced enormous opportunities for Brewers. Each of these materials is added as late as possible in the process. Still, though, most of the hopping of beers is carried out in the brewhouse, the subject of the next chapter.

6

Cooking and Chilling

The Brewhouse

The production of beer can be conveniently split into a "hot end" and a "cold end." The former takes place in the brewhouse (fig. 6.1), the latter in the fermentation cellar and all points downstream therefrom. Strictly speaking, *brewing* is what happens in the brewhouse, a process designed to convert malt and any adjunct materials into wort, which forms the feedstock that yeast converts into alcohol. Traditionally (and still extensively) it is in the brewhouse that the hops are introduced into the process.

Chemistry and Biochemistry in the Brewhouse

Wort needs to have various features: first, it must contain sugars that the yeast is capable of fermenting into alcohol. These sugars are the energy source that the yeast needs to support its growth. It is not a question of "any old" sugars: the balance of different types can have a profound effect on the way yeast performs and how efficiently it converts them into alcohol. Moreover, the type of sugar influences the balance of flavor compounds that the yeast produces, and therefore the flavor of the beer.

Second, the yeast requires from wort the building blocks that it will use to synthesize its proteins. These are the amino acids and peptides (usually referred to as free amino nitrogen, or FAN) that in turn are produced during malting and mashing by the breakdown of barley proteins. Once again, they must be in balance. The relative proportions of the different amino acids influences yeast behavior, as does the ratio of sugars to amino acids.

Figure 6.1 *A modern brewhouse. This one is at Sierra Nevada Brewing Company in Chico, California. Courtesy of Sierra Nevada Brewing Company.*

The balance of sugars and FAN is determined by what happens in the brewhouse. It is also within the brewhouse that the Brewer establishes the right salt balance in the wort, whether or not the wort will contain the necessary levels of sulfur and other elements that the yeast depends on, and whether the beer will contain the necessary levels of foaming materials. And it is here that a range of undesirable materials is eliminated, including unpleasant flavors and materials that can promote turbidity in beer.

With the development of ingredients such as preisomerized hop extracts, it is no longer the case that bitterness is necessarily determined in the brewhouse, but this is still the practice in a great many breweries. Color, too, can be modified downstream, but for as long as the brewhouse is a standard feature of brewery operations, it will have a major impact on all aspects of downstream performance and product quality.

A simple description follows of the enzymic processes that are involved in mashing (and that have to some extent already begun in malting). The appendix may be useful at this point for those for whom enzymology is a mystery.

The Breakdown of Starch

As shown in chapter 4, it is generally important for efficient brewhouse operation that a malt has had its cell walls comprehensively degraded, as well as perhaps half of its protein. It is essential, however, that the bulk of the starch within the endosperm survive malting, for this is what the Brewer uses as a source of fermentable sugar to “feed” the yeast. The remarkable fact is that this is seldom a problem and that starch by and large does survive the malting process, even though the enzymes needed to disrupt it are plentiful. This tells us that starch is a relatively tough nut to crack. If it is to be broken down in the relatively short time frames available to a brewer (frequently no more than an hour in the mash), then it must first be “gelatinized.” When starch granules are heated, the molecules that compose them “melt,” and the granular structure disaggregates. This melting occurs at different temperatures, depending on the origin of the starch. Barley starch exists in two populations: large granules, which are generally between 15 and 20 μm in size (reminder: a micrometer is a thousandth of a millimeter), and small granules, which are less than 6 μm in diameter. Although there are 5–10 times more small granules than large ones, the latter account for more than 85% of the total starch by weight. The large granules gelatinize at 58–62°C, whereas the temperature must be raised to 68°C to melt the smaller ones. If the small granules are not degraded, they cause substantial problems for the Brewer. In practice, they don’t survive in significant quantities into a well-modified malt, showing that despite their higher gelatinization temperature they are more readily consumed in germination, probably because of their much smaller size—they are less of a “mouthful” for the amylases.

To achieve gelatinization, then, mashing usually includes a “conversion” stage, typically at 65°C, for 50–60 minutes. The starch will be gelatinized almost immediately, rendering it accessible to attack by the amylase enzymes, which rapidly hydrolyze it.

Rice starch gelatinizes over the range 64–78°C and corn starch 62–74°C. These cereals, if they are used as adjuncts in the brewery, must therefore be “cooked,” and the brewhouse that will use them will have a cereal cooker alongside the mash vessel. Wheat starch gelatinizes at temperatures similar to barley starch, and therefore wheat flour can be used directly in the mash.

Within the starch granules there are two other populations of starch: the amylose and the amylopectin. Both of these molecules are polymers of glucose units linked together in chains. They differ in that the molecules of amylose, which typically amount to 25–30% of the total starch, are linear chains of perhaps 1,800 glucoses, whereas amylopectin molecules consist of many much shorter chains linked through branch points. The significance of this is that they require different enzymes to chop them up.

The major starch-degrading enzyme in malt is α-amylase. It’s very similar to the enzyme found in human saliva—indeed, in some societies fermentation of alcoholic beverages starts with the starch being digested by a generous donation of saliva from the “brewer.” (I’m not aware of any beer brewers presently applying this technique!) The enzyme α-amylase attacks at ran-dom in the middle of the amylose and amylopectin, releasing some small sugars but primarily short chain molecules (called dextrins). The next enzyme is the β-amylase, which starts at one end of the dextrin molecules, chopping off two glucoses at a time. (Two glucoses joined together represent the sugar maltose, so named because it is the major sugar found in mashed malt.)

With amylose, the combined action of these two amylases leads to a mixture of sugars that is completely fermentable. Such is not the case with amylopectin. Its branch points are not chopped up by either of these amylases, and when β-amylase encounters them, it can't get past them. A third enzyme is needed, one whose role is to hydrolyze the branches: it is called limit dextrinase, but it is only produced late in the germination process. Moreover, it is bound up with other components from malt that limit its activity. The outcome is that conventionally mashed malt doesn't produce totally fermentable wort, with perhaps 20% of the sugar being tied up in a dextrin form. Most beers worldwide contain residual dextrin for this reason—and it is believed is that these dextrins contribute to the body of beer. The so-called diet or light beers, however, contain no residual sugar. The Brewer may have added heat-stable enzymes (from microbial sources such as *Aspergillus,* a food-grade organism used, for example, in brewing sake), which are capable of chopping up the branch points in amylopectin. As a result of the combined efforts of the malt-derived and the exogenous enzymes, all of the starch is converted into fermentable sugar. Alternatively, a much more complex mashing regime may be used, to maximize the opportunity for the various starch-degrading enzymes to act, perhaps followed by the inclusion of a small charge of an extract of very gently kilned malt in the fermenter so as to introduce more of the enzymes needed for completion of starch degradation.

Some of the low-alcohol beers in the market, containing perhaps 1–2% alcohol (by volume), are produced using a technique called "high-temperature mashing." If the malt is mashed at a higher-than-normal temperature, say 72°C, then the β-amylase is quickly destroyed, and far less maltose is produced in the wort. Most of the starch is converted only as far as nonfermentable dextrins, so the resultant wort contains much less sugar that is transposable by yeast into alcohol.

The Breakdown of Cell Walls

Most Brewers look to the Maltster to provide them with malt that has had its cell walls comprehensively removed. In practice, most malts have some cell wall material remaining, either intact or partially degraded, and this can cause problems.

The cell walls of barley contain two major polysaccharides: the β-glucans and the pentosans. The former, which accounts for some 75% of the wall, is a straight chain polymer of glucose, just like amylose. The difference is in the way the glucoses are joined together. This means that the properties of β-glucans and starch are very different, as well as that a totally distinct set of enzymes is needed to break down the two materials. Pentosan is also a sugar polymer, but this time the backbone is a chain of xylose units, and side-chains consist of another sugar, arabinose.

It is generally supposed (perhaps erroneously) that the pentosans don't get substantially degraded during malting, nor do they get extracted into wort during mashing. It is the β-glucans about which the Brewer is paranoid.

The β-glucan molecule gives very viscous solutions. If it is not broken down in malting or mashing, it will be extracted into wort to cause all manner of problems for the Brewer because of this viscosity effect: it will slow down the rate at which the wort can be separated from the spent grains (see hereafter) and, because it will survive fermentation intact, it will get into beer and greatly reduce rates of beer filtration. As beer is filtered around 0°C and viscosity increases as temperature is lowered, this is a particular problem. Not only this, but the solubility of β-glucan is reduced as the temperature falls, and if this material survives into beers then there is the risk of sediment formation in beers stored in refrigerators. This is a particular problem with stronger beers: because they contain more alcohol, they are likely to have been made from more concentrated worts (in other words, more malt per unit volume). In turn, this greater "malt contribution" will yield higher levels of molecules such as β-glucans to the beer. The situation is compounded further by the fact that alcohol itself acts as a precipitant, increasing the likelihood that the β-glucan will collect in the bottom of the bottle as fluffy sediment.

The most important enzyme from malt that degrades this troublesome polymer is β-glucanase. It is produced in ample quantities early on in germination, and, providing it gets distributed through the starchy endosperm in malting, it is capable of removing most of the β-glucan. Most but not all. The major problem with this enzyme is that it is extremely sensitive to heat. At 65°C (the temperature used to gelatinize malt starch), this enzyme is destroyed in a couple of minutes. For this reason many brewers commence their mashing operation at a relatively low temperature (say 45–50°C) to enable the β-glucanase to act, and then, after 20 minutes or so, the temperature is ramped up to 65°C. Alternatively, a heat-resistant, food-grade β-glucanase, perhaps from *Bacillus subtilis* or *Penicillium funiculosum,* can be added at the conversion temperature.

The Breakdown of Protein

Just as for cell walls, it is the malting operation that is most significant for protein hydrolysis (or proteolysis). Unlike the case for β-glucans, the Brewer does not want total degradation of protein, for some of it is needed to form the backbone of the foam on the beer. However, there does need to be generation of low-molecular-weight products, primarily the amino acids, that the yeast will require for synthesis of its own proteins. Proteolysis is also necessary to get rid of proteins that contribute to haze formation in beer.

Barley contains a range of protein types, broadly classified by their solubility properties. Primarily they can be divided into the water-insoluble storage proteins called hordeins and the water-soluble albumins, among which are the enzymes.

Proteolysis in the context of malting and mashing is primarily involved with the degradation of the hordeins. Two types of enzyme are involved. The proteinases attack these proteins in the middle of the molecule, releasing shorter linear polypeptide chains of amino acids. These shorter chains are then the substrate for a second enzyme, called carboxypeptidase, which starts at one end of the chain, chopping off one amino acid at a time.

Carboxypeptidase is quite heat resistant, but the proteinases aren't. Once again, then, Brewers may start their mash at a lower temperature to deal with protein, as well as β-glucan. This period of mashing is frequently referred to as a "proteolytic stand." However, there is increasing evidence that inhibitors that are extracted from the malt alongside the enzymes block much of the potential protein hydrolysis in a mash. Within the grain the natural control mechanisms regulate the extent to which the inhibitors are able to interact with the enzymes. Once extracted, though, in what is literally a "mishmash," the inhibitors are freed from these restraints, so proteolysis is limited.

Water

Malt is only one part of the equation in mashing; the other is water. It, too, must be right. The brewing process demands substantially more water than that which ends up in the beer. Large amounts are needed for cleaning purposes and for raising steam, which is the major heating element in most breweries. Most Brewers have made tremendous steps in reducing their water consumption, but the poorer performers may still use as many as 20 liters of water for every liter of beer they produce.

Quite apart from the obvious requirements, such as an absence of taints and of hazardous components and an adherence to all requirements as a potable supply (to satisfy all of which a Brewer may treat all water by procedures such as charcoal filtration and ultrafiltration), the water must have the correct balance of ions. Traditionally, breweries producing top-fermented ales were established in areas, such as Burton-on-Trent in England, where the level of calcium in water is relatively high (about 350 ppm). This compares with a calcium level of less than 10 ppm in Pilsen, a place famed for its bottom-fermented lagers. In many places in the world, the salt composition of the water (often brewers call it "liquor") is adjusted to match that first used by the monks in Burton in the year 1295. This adjustment process is called Burtonization. Sometimes the brewer will simply add the appropriate blend of salts to achieve this specification. To match Pilsen-type water it is necessary to remove existing dissolved ions by deionization.

Water may originate either from the Brewer's own well or from a municipal supply. The former is more likely to have a composition that "marries" with the nature of the beer brewed in a longstanding brewery.

Calcium in brewing water plays several roles. First of all, it promotes the action of α-amylase. It reacts with phosphate in the malt to lower the pH to the appropriate level for brewing. In addition, it precipitates another natural component of malt, oxalic acid, which otherwise would come through into the beer and cause problems such as the blocking of dispense pipes ("beer stone"). Calcium also promotes the flocculation of yeast.

Many Brewers (as already mentioned) worry about two other ions contributed by water, chloride and sulfate.

Adjuncts

A Brewer may substitute other things for a proportion of the malt, for various reasons; the alternative sources of extract are called adjuncts. Some adjuncts are used because they introduce necessary characteristics to a beer. For instance, the intense flavor of Guinness reflects the use of roasted barleys and malts in the grist. At the other extreme, some of the delicate character of Budweiser clearly originates in the rice that it contains, and the use of this material also allows for the product to have good taste along with a very pale color. Some Brewers will use adjuncts such as wheat flour because they believe they provide foam-enhancing substances to beer.

As often as not, though, adjuncts are employed for reasons of economy: if the unit cost of fermentable carbohydrate is lower in an adjunct than it is from malt, then it makes sense to replace a proportion of the malt, provided that it doesn't jeopardize any element of product quality, notably flavor. Some Brewers use corn products in the brewhouse. As already mentioned, corn and rice starches have higher gelatinization temperatures than barley starch and need to be "cooked." Most commonly, hydrolyzed corn syrup or sucrose, both of which comprise ready-formed sugars that don't require an enzymatic stage in the brewhouse, will be used to supplement wort at the boiling stage in the kettle. In all cases the Brewer must perform its calculations carefully: if an adjunct is intended simply as a cheaper source of extract, it must be remembered that the additional processing costs for handling a more intransigent material may offset any potential savings. By using sugars and syrups in the kettle, the Brewer can extend the volumes of wort produced without investing in extra mashing and lautering capacity.

In the United States, adjunct is some 38% of the total grist bill. Almost half of the adjunct used is corn grits, and just under a third is rice. Syrups and sugars amount to just over a fifth of the total. In the United Kingdom, malt usage is higher, at some 80% of the total grist; hydrolyzed corn syrup is the most frequently used adjunct.

The Brewhouse

Milling

Most frequently malt is ground using roller mills; the malt is passed through one, two, or three pairs of rollers. The aim is to produce a particle distribution that is best suited to that particular brewhouse and for the type of malt used. For example, if the husk of the malt is required as a filter bed for the separation of the wort, then it will be necessary to have a setup that enables survival of this tissue, while at the same time milling the starchy endosperm to a consistency fine enough to allow easy access of water for its solvation. If the malt is relatively well modified, it will need less intense milling than would relatively undermodified malt to generate the same particle size distribution.

Generally speaking, the more rolls there are on a mill, the greater its flexibility. The Brewer inspects the milled grist, using a sieve to screen it into its various sized components, and the roll settings are adjusted if its particle distribution is felt to be suboptimal.

Some Brewers employ wet milling, in which the malt is steeped in water before milling begins. It is believed that the hydration of the husk lessens the risk of its damage during milling. Increasingly common is the use of hammer-milling, but only with modern mash separation processes such as the mash filter, which don't require the husk as a filter bed.

Mashing

This is the enzymatic stage of the brewhouse operation. The milled malt is mixed intimately with the water, which enables enzymes to start acting. Essential requirements of this stage are that the particles be efficiently hydrated and that careful control be exerted over times and temperatures. It is by manipulating these that the Brewer is able to influence the efficiency with which the malt is extracted.

Modern mashing vessels (still sometimes called *mash tuns* or *mash mixers*) are fabricated from stainless steel. This is the norm for all brewery vessels, as it makes for robustness and for ready cleaning by so-called cleaning-in-place (CIP) systems. To achieve intimate mixing of the milled grist and the water, they are mixed using a "foremasher" on their way into the mash conversion vessel (fig. 6.2). Rousers provide further mixing within the mash vessel (fig. 6.3). It isn't simply a matter of thrashing the mixture about. Excessive physical damage to particles will slow down the subsequent wort separation stage and lead to unacceptably turbid worts, but it will also cause far greater uptake of air into the mash. It is now often said that this can promote staling in the subsequent beer.

Modern mash mixers are jacketed; steam is used to heat up the contents of the vessel. As already mentioned, mashing may commence at a relatively low temperature (say 45°C) to enable the more heat-sensitive enzymes, such as β-glucanase, to do their work. Once this "rest" is complete, the steam will be put through the jacket to bring up the temperature, perhaps at 1°C per minute, to that required for gelatinization of starch.

Typical practice may be to introduce a proportion of water into the mash tun, sufficient to cover the agitator, before running in the grist/water mix via the premasher. Grist entry is likely nowadays to happen near the base of the vessel, in order to minimize air uptake. Various additions may be made. For instance, certain salts may be added if there is a need, for example, to adjust the chloride-sulfate balance. Calcium may be added in order to lower the pH of the mash (see the appendix): ideally a mash should be of pH 5.2–5.6 for the appropriate balance to be struck between the various reactions that are occurring. Alternatively, acids may be used directly or introduced indirectly: for instance, in Germany, lactic acid bacteria (so called because of their main excretion product) are used to acidify the mashes "naturally." Extra enzymes might be introduced in some countries, most often this is a heat-resistant β-glucanase to supplement the more sensitive enzyme from malt.

Cereal cookers used to gelatinize the starch in certain adjuncts are operated analogously to mash tuns, though of course the temperatures employed are higher.

Wort Separation

Once the enzymes have completed their job in the mash, it is time to separate the resultant wort from the residual ("spent") grains. In many ways this is the most skilled part of the brewing operation. The aim is to produce a wort that is referred to as "bright": in other words, does not contain lots of

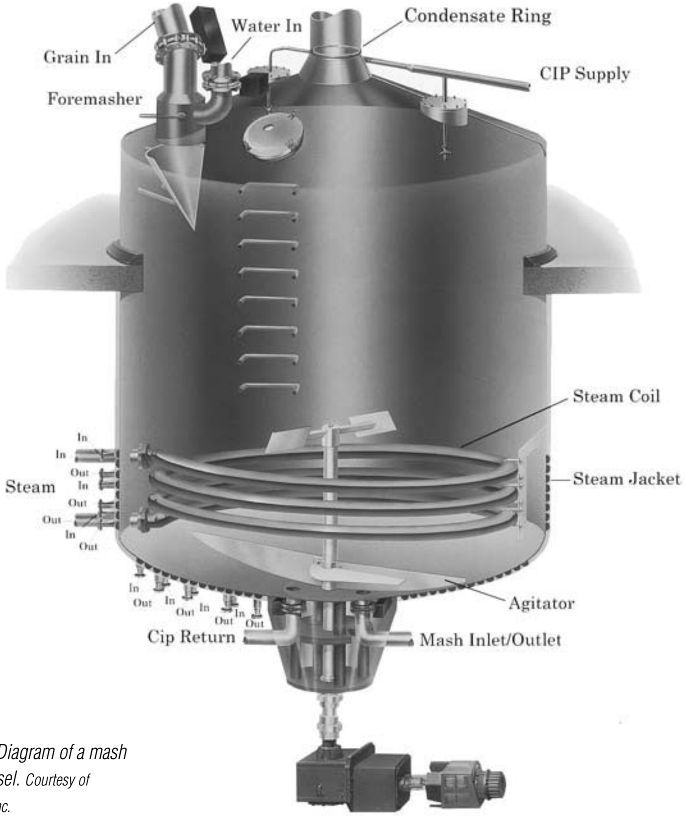


Figure 6.2 *Diagram of a mash conversion vessel. Courtesy of Anheuser-Busch, Inc.*

Figure 6.3 *Inside a mash conversion vessel. The agitator is designed to ensure efficient and homogeneous mixing. Courtesy of Briggs of Burton.*

insoluble particles that may present great difficulties later on. The challenge is to achieve this without sacrificing wort, thereby limiting yields. Furthermore, this has to be achieved within a limited time period, for a Brewer will want to put several brews through the brewhouse each day.

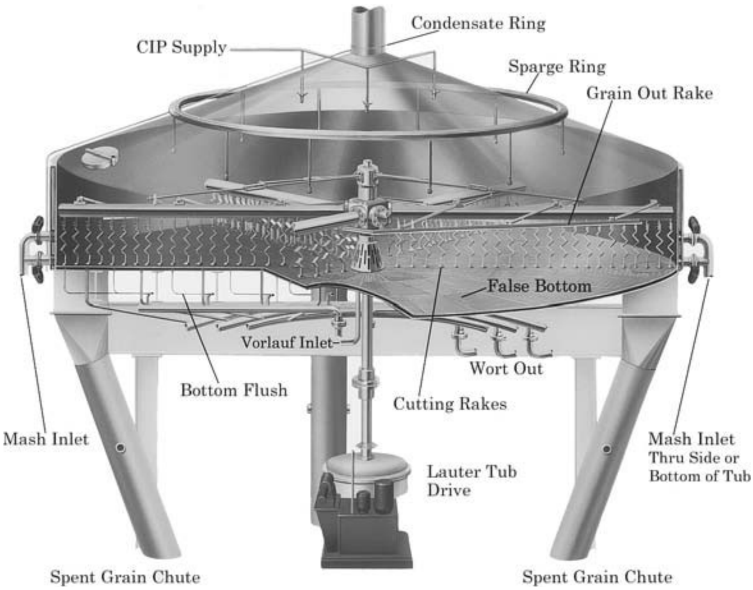
The majority of breweries in the world use a lauter tun (or tub) for this purpose (fig. 6.4). In newer brewhouses, though, you are likely to find a mash filter.

The science of wort separation is fascinating and is based on an equation developed by Darcy:

$$\text{rate of liquid flow} = \frac{\text{pressure} \times \text{bed permeability} \times \text{filtration area}}{\text{bed depth} \times \text{wort viscosity}}$$

Basically, it means that the wort will be recovered more quickly if the vessel used to carry out separation has a large surface area and is shallow (i.e., the distance through the bed is short). Low viscosities (i.e., low β-glucan levels) will help, as will the application of pressure. The "permeability" depends on the particle characteristics of the bed. The best analogy would be to sand and clay. Sand comprises relatively large particles, whereas the particles of clay are far smaller. To pass through clay, water has to take a far more circuitous route than is the case for sand. Thus big particles tend to present less of an impediment to liquid flow than small ones. At the end of mashing and during sparging, relatively high temperatures (e.g., 76–78°C) are main-

Figure 6.4 *A lauter tun. Courtesy of Anheuser-Busch, Inc.*



tained. In part this is because of the inverse relationship between temperature and viscosity, but it is also known that smaller particles agglomerate to form larger ones at higher temperatures.

Lauter Tun. Generally this is a straight-sided round vessel with a slotted or wedged wire base and runoff pipes through which the wort is recovered. In addition, within the vessel there are arms that can be rotated around a central axis (fig. 6.5). These arms carry vertical knives that are used, when appropriate, to slice through the grain bed and facilitate runoff of the wort. The Brewer first runs hot water (at about 77°C) into the vessel such that it rises to an inch or so above the false bottom. This ensures that no air is trapped under the plates and serves to "cushion" the mash. The mash will then be transferred carefully from the mash tun to the bottom of the vessel, again to minimize oxygen uptake, and the knives will be used to ensure that the bed is even. Hot liquor is used to "rinse out" the mash tun and delivery pipes. The depth of the grain bed is unlikely to be more than 18 inches (see the Darcy equation).

After a "rest" of perhaps 30 minutes, the initial stage is to run off this wort from the base of the vessel and recycle into the vessel, so that it can be clarified. After 10 to 20 minutes of this so-called vorlauf process, the wort is diverted to the kettle and wort collection proper is started. This wort is at its most concentrated.

The remainder of the process is an exercise in running off as concentrated wort as possible within the timeframe available. More hot (77°C) liquor (the "sparge") is sprayed onto the grains so that the sugars and other dissolved

Figure 6.5 *The "gear" inside a lauter tun. Courtesy of Briggs of Burton.*

materials are not left trapped in the spent grains. The knives are used as sparingly and carefully as possible so as not to damage grains and thereby make small particles that will "clog" the system or render the wort turbid, or "dirty."

Another factor that the Brewer must consider is the strength of the wort that is needed in the fermenter. If the Brewer is intending to brew a very strong beer, then clearly the wort must be rich in sugars. This limits the amount of sparge liquor that can be used in the lauter tun. Some brewers will collect separately in one kettle the initial stronger worts running off from the lauter tun, using this for stronger brews, before collecting subsequent weaker worts in a second kettle.

When the kettle is full, there may still be some wort left with the grains. Time permitting, this will be run off for use as "mashing-in" liquor for subsequent brews, a process referred to as "weak wort recycling." The Brewer needs to be careful, though: when the worts are very weak there is an increased tendency to extract tannins out of the grains, and these can cause clarity and astringency problems in beer.

At the completion of lautering, grain-out doors in the base of the vessel are opened, and the cutting machinery is used to drive the grains out. Almost without exception, spent grains are trucked off-site as fast as possible (they readily "spoil") for direct use as cattle feed.

Mash Filters. These operate by using plates of polypropylene to filter the liquid wort from the residual grains. Accordingly, the husk serves no purpose as a filter medium, and particle sizes are irrelevant. The high pressures that can be used overcome the reduced permeability that is due to smaller particle sizes (the sand-versus-clay analogy I used earlier). Furthermore, the grains bed depth is particularly shallow, being nothing more than the distance between the adjacent plates, which cumulatively amount to a huge surface area. The chambers of the press are first filled with liquor, which is then replaced by mash with filling times of less than 30 minutes. During this time the first worts are recovered through the plates. Once full, the outlet valves are closed. The filter is then given a gentle compression to collect more wort. This is followed by sparging to get a uniform distribution of liquor across the filter bed, then a further compression to force out the remaining wort. Using mash filters, wort separation can be completed in 50 minutes rather than the periods of up to two hours needed for lautering. Accordingly, the Brewer can achieve more brews per day.

Wort Boiling

The boiling stage serves various functions. First, the intense heat inactivates any of the more robust enzymes that may have survived mashing and wort separation and sterilizes the wort, eliminating any organisms that might jeopardize the subsequent good work of the yeast. Second, proteins tend to coagulate when you heat them strongly, as anyone who has boiled an egg will appreciate, and so, in wort boiling, proteins are removed that might otherwise precipitate out in the beer as haze. They crosslink with tannins (polyphenols) from malt and hops and produce what is known as "hot break." Third, the α-acids from hops are isomerized into the bittering principles, and other flavor changes take place, including the driving-off of undesirable characters originating from hops and malt. The color of wort increases during boiling through melanoidin reactions (see chapter 3). Finally, as water is of course driven off as steam during boiling, the wort becomes more concentrated.

Most Brewers will tend to use a boil of between one and two hours, evaporating some 4% of the wort per hour. Clearly, this is a very energy-intensive stage of the brewing process, and every effort is made to conserve heat input and loss. Kettles come in a myriad of shapes and sizes, but in modern breweries they are stainless steel, straight-sided, and curved-bottomed and are very likely to be heated using an "external" heat exchanger called a "calandria" (fig. 6.6). Alternatively, the calandria may be inside the vessel (fig. 6.7).Efficient boiling demands turbulent conditions in the vessel and thorough mixing: the calandria, which employs convective mixing of the system, enables this.

Figure 6.6 *A kettle (right) with external calandria (left). Courtesy of Briggs of Burton.*

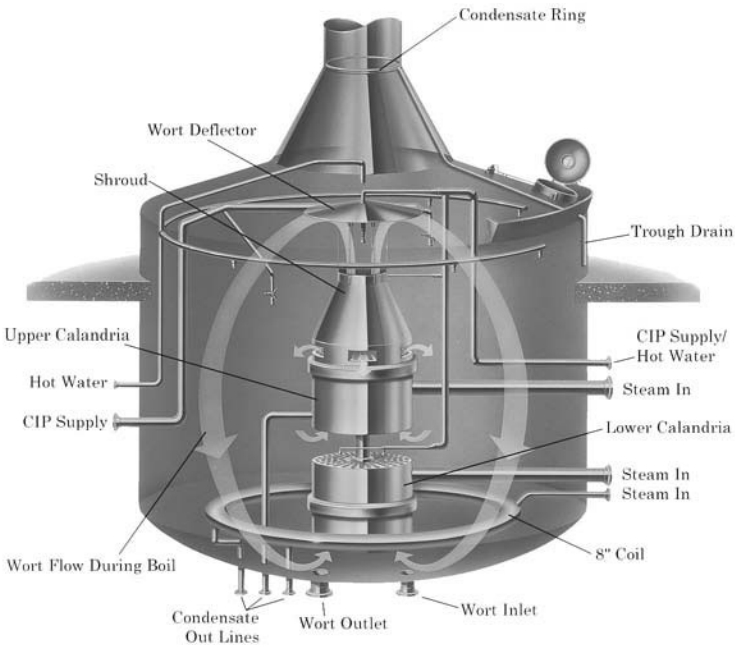


Figure 6.7 *Diagram of a wort kettle, showing how good agitation of the wort is achieved using the calandria, which is in this instance internal, and a spreading plate (deflector).* *Courtesy of Anheuser-Busch, Inc.*

The significance of the boiling stage for beer flavor should not be underestimated. Apart from the driving-off of unpleasant grainy characters that originate in the grist, certain other substances are actually produced during boiling and, at least in part, they can be desirable. Perhaps the best studied of these materials is DMS.

As I mentioned in chapter 3, opinion is divided on whether DMS is desirable in beer or not. I know one brewer who firmly believes that a level of 50–60 ppb of DMS makes a substantial contribution to lager quality and another who gets paranoid if the level rises above 20 ppb, which is below the level of detection by the nose. The challenge therefore is to deliver the desired level of DMS to the appropriate beer.

All of the DMS in beer originates from a precursor in the germinating embryo of malted barley. This precursor, sometimes called DMSP (P for precursor) or SMM (because the material is known to be S-methylmethionine), is increased to a greater extent if embryo development is substantial. Thus, if a malt is well modified (see chapter 4), it will tend to contain more precursor. The most significant property of SMM is that it is quite sensitive to heat: when it breaks down, it produces DMS. And so, whenever there is a heating stage during malting and brewing, SMM is degraded.

The first heating stage in the conversion of barley into beer is the kilning of malt: the more intense the kilning, the greater the breakdown of SMM. The DMS produced is largely driven off with the flue gases. For this reason, there is more SMM in lager malts than ale malts, because the latter are kilned more intensely. In other words, the DMS potential entering into lager brews is greater than in ale brews, so lagers tend to contain DMS, whereas ales don't.

The next significant heating stage is the boil. Yes, the mashing and wort separation stages involve quite a bit of heating, but it's only when the temperature gets much above 80°C that SMM breakdown occurs. In the boil, though, breakdown of SMM (which will have been extracted from the malt in the mash) is quite rapid. The more vigorous and extensive the boil, the more SMM breaks down, and the DMS released goes up the chimney.

Brewers not wanting DMS in their lager will not only have ensured that the malt had low DMS potential (see chapter 4), but will also tend to demand a prolonged and vigorous boil. Those requiring some DMS will ensure that there is ample SMM in the malt and will throttle back the boil, to ensure that some of the precursor survives to the next stage in the process.

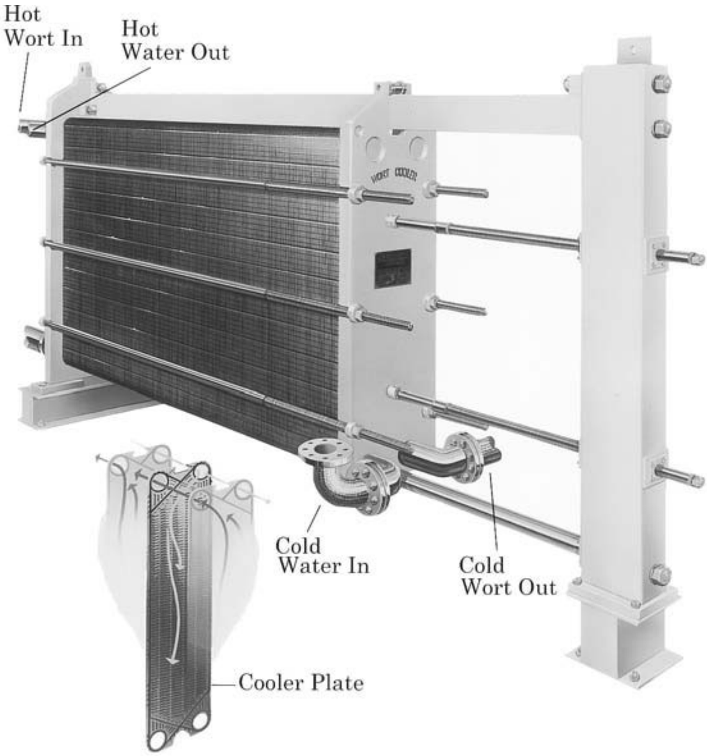
Figure 6.8 *Diagram of a hot wort receiver ("whirlpool"). Courtesy of Anheuser-Busch, Inc.*

Removing Trub

Various devices have been used to separate the trub and other residual solids from boiled wort. For those brewers using whole-leaf hops, this stage is completed using a "hop back," a vessel analogous to a lauter tun, in which the residual plant material forms a filter bed. Such approaches are not applicable when hop pellets and hop extracts are used. Centrifuges have been used to remove wort solids, but much more common is the "whirlpool" (fig. 6.8). These are cylindrical tanks, approximately 5 meters in diameter, into which wort is pumped tangentially through an opening that is between 0.5 and 1.0 meters above the base. The wort is set into a rotational flux, which forces the trub into a conical pile at the center of the vessel. After a period of perhaps one hour, the wort is drawn off through pipes at the base of the vessel, in such a way as not to disturb the collected trub.

The precipitation of insoluble materials in the brewhouse is sometimes promoted by the addition of materials called carrageenans, which are extracted from red and brown seaweeds. Carrageenans are polysaccharides (polymers

Figure 6.9 *A wort cooler ("paraflow"). Courtesy of Anheuser-Busch, Inc.*



of sugars); they stick onto the solids in beer, increasing their size and thereby making them more sedimentary.

For those Brewers aiming for some DMS in their lagers, the whirlpool stage is critical. The precursor that they ensured survived the boil will continue to be broken down here. Temperatures are high enough for the SMM to degrade, but the conditions are far less turbulent. The DMS released is not driven off but remains dissolved in the wort. During fermentation (see chapter 7), much of this DMS will be driven off with the carbon dioxide produced by yeast—but some will survive. The trick is to ensure that the right amount of SMM survives the boil, to convert it all into DMS in the whirlpool and to bring into the fermenter the level of DMS in wort that will leave the desired quantity of DMS in the beer after the proportion that will be lost with CO_2 has been accounted for. (Actually, the story isn't quite as simple as this—and I'll touch on it again in chapter 7.)

Wort Cooling

The whirlpool may be insulated, but if not, the wort temperature may fall to 85°C or less. Even so, that is far too hot for the survival of yeast. For this reason, the final stage before fermentation must be cooling. Customarily this is achieved using plate heat exchangers (fig. 6.9). The wort flows turbulently on one side of the plates, with a cooling medium (chilled water, brine, ammonia, or glycol solution) on the other. When wort is chilled, more solids may precipitate out: the so-called cold break. These solids consist of protein but also some lipids. Opinion differs among Brewers on the relative merits of this material (see chapter 7). Sometimes it is removed by flocculation, flotation, centrifugation, or filtration.

The final stage in wort production en route to the fermenters is the introduction of oxygen, which yeasts require for healthy growth, as the next chapter will show.

The sequence of events in the brewhouse, then, is complex, and it is geared toward generating, in the highest possible yield, a nutritious wort that the yeast will grow on to make the beer that the Brewer wants. The composition of that beer, and therefore whether it is good or bad, is inherently dependent on the behavior of the yeast, which in turn reflects the quality of the wort, as we shall see in the next chapter.

7

Goddisgoode

Yeast and Fermentation

The common denominator in the production of all alcoholic beverages is fermentation. For beer this involves the conversion of sugars, derived primarily from malt, into ethanol (ethyl alcohol or, for most people, just "alcohol") by the yeast, *Saccharomyces cerevisiae,* the "mysterious" properties of which in medieval times caused it to be known as "goddisgoode." The nature of any alcoholic drink is determined not only by the yeast strain used to produce it, but also by the substrate (feedstock) that the yeast is converting. Thus wines have the character they do because of the strains of yeast used in wineries, and because of the grape-based substrate. Wines are prized (or otherwise) because of the vintage of grape they may enjoy. Beers, too, have the character they do because of the subtle interaction between carefully selected "brewing strains" of yeast and the malt and hops that come together as wort.

Brewing Yeast

Saccharomyces cerevisiae, then, *is* a busy beast. Apart from being the workhorse of the brewery, it is responsible for the production of cider, wine, spirits, and some other alcoholic beverages. And as every cook knows, it is essential for the production of life's other staple food, bread.

The reader needs to be aware that it is not the same strains of *Saccharomyces cerevisiae* that do all these tasks. Just as it takes humans with all manner of skills to make up society, so is it a collection of strains of *S. cerevis-*

iae that tackle the range of tasks just mentioned. Yes, brewing strains can be used to ferment grape must and make passable wine, and wine yeasts can be used to ferment wort, with some interesting products. The fact remains, though, that the character of a beer is in large part established by the yeast that is used to make it. That is why Brewers guard their strains carefully—just as any skilled workman looks after the tools of his trade.

The Structure of Yeast

Yeast is a single-celled organism, about 10 μm in diameter. Bacteria also comprise one cell, but yeast are substantially more complex and, like all so-called eukaryotic organisms, the cell is divided up into organelles, each with its own job of work.

The heart of a cell is its nucleus, within which is stored much of the genetic information held in deoxyribonucleic acid (DNA). In turn the DNA is coiled up into chromosomes, of which *S. cerevisiae* has 16. The strains of this organism that have been used for much of the laboratory research over the years contain just one copy of each chromosome: they are said to be haploid. Other yeasts are diploid, with two copies of the genome. Brewing yeasts are aneuploid, containing approximately three copies of each chromosome. I say "approximately" because the exact number of copies of individual chromosomes present may differ. The fact that brewing yeasts contain more than a single copy of each gene makes them quite stable: they can tolerate loss of one of the copies of a gene simply because they can fall back on the other copies. This is good news for Brewers, as their yeasts are consistent for many generations.

The yeast cell is surrounded by a wall, within which is a membrane, the so-called plasma membrane. The wall offers strength to the cell, protecting the rather more delicate membrane beneath it. It also plays a major role in cell-cell interactions: it is through links between walls and calcium that cells flocculate and migrate either to the surface or base of a fermenting vessel. This has major implications for brewing practice, for instance the procedure that the Brewer will use to separate the yeast from the "green" beer at the end of fermentation.

The function of the membrane is to regulate what does and does not get into and out of the cell. Although a yeast has its intracellular food reserves, it depends on materials in its growth medium (in the case of beer, the growth medium is wort) for its survival and growth. The composition of the membrane influences what (and how readily) molecules such as sugars and amino acids move into the cell. The membrane has a similar influence on what leaves the cell.

One other organelle worthy of mention is the mitochondrion. This is the part of a eukaryotic cell largely responsible for energy generation by respiration. However, the requirement for mitochondria by yeast in brewery fermentations is the subject of controversy. We know that when yeast converts sugar into alcohol it is an anaerobic process. Yeast, though, can also use sugar via a respiration route. Only in the latter case should active mitochondria be needed. But what if these organelles have some other function apart from energy generation? In fact, mitochondria do perform some other roles; for instance, they are involved in the synthesis of certain amino acids. And so they are to be found in brewing yeast when it ferments wort, although they have a peculiarly elongated shape somewhat different from that found when yeast is growing in the presence of oxygen.

Like other single-celled organisms, brewing yeast reproduces by cell division. The daughter cell grows from the mother cell as a bud, before separating off as a distinct cell, leaving a "bud scar" behind on the mother cell (see fig. 7.1). An indication of the age of a yeast cell is obtained by counting the number of bud scars, which can be as many as 40–50. Yeast can also enjoy a healthy sex life, though perhaps sadly for it, this is a less favored means of reproduction.

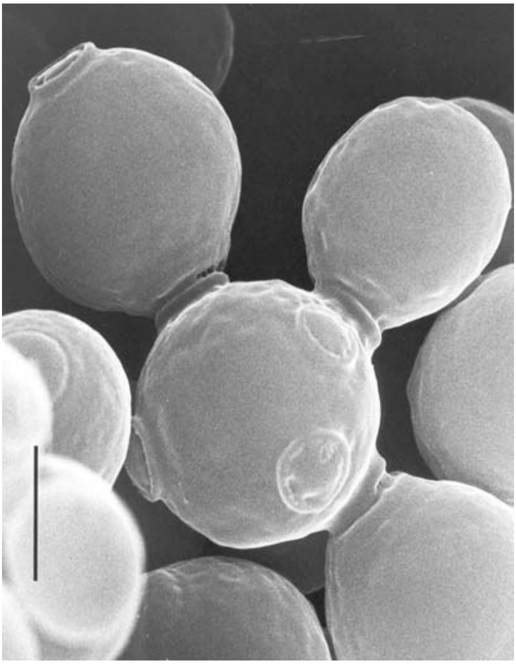


Figure 7.1 *Yeast as seen under an electron microscope. The budding and bud scars are clearly visible. Courtesy of Dr. Alastair Pringle, Anheuser-Busch, Inc.*

Classification of Brewing Yeasts

Until relatively recently, brewing yeasts were divided into two species: *Saccharomyces cerevisiae* and *Saccharomyces carlsbergensis*. The latter was named, of course, by the pioneer of pure yeast use, Emil Christian Hansen. Carlsberg, the company to which he introduced this technology in 1883, still proudly uses this terminology. Most others have used the term *Saccharomyces uvarum* instead of *S. carlsbergensis* for those yeasts that do their job at relatively low temperatures (typically 6°C and 15°C) and that, after flocculating, drop to the bottom of the fermenter and that are traditionally used in the production of lager-style beers. The name *Saccharomyces cerevisiae* has been reserved for yeasts that make ales at temperatures in the range 18 to 22°C and that collect at the surface of the fermenting vessel. It is, indeed, possible to differentiate between yeasts in either category, notably by the fact that yeasts classified as *S. uvarum* can grow on the sugar melibiose, whereas *S. cerevisiae* can't.

Since the early 1980s, though, taxonomists have declared that all brewing yeasts should be classified as *S. cerevisiae,* on the basis of the properties of their DNA. And yes, there are many different strains within this classification, hence the variety of products we can enjoy.

Because brewing strains differ so much in their properties and behavior, it is important that a Brewer knows which strain it is dealing with. For instance, a company may brew the same brand in several different breweries and distribute the relevant yeast from a central repository. The sender and the recipient should both run checks to make sure that the yeast is the right one. Within a given brewery, too, several yeast strains may be used, to make a range of products. It is critical to be able to distinguish them. Good housekeeping only goes so far: from time to time a check needs to be run to confirm that the correct yeast is being used. This problem is particularly acute where a brewery performs franchise brewing. I know of one major brewery, for instance, that brews at least four major international lager brands for four different companies. Not only is that brewery trusted with custodianship of the respective yeasts, it is also under intense pressure to make sure that there are no mixups or crosscontaminations.

There are those who downplay the significance of yeast strain, and indeed there is clear evidence that certain brands can be successfully made with yeasts associated with a totally distinct brand. Indeed, there are opportunities for rationalization of yeast strains—but this demands rigorous trials to ensure that the desired beer is produced (and will continue to consistently display the required quality characteristics) and that there are no "funnies" in production. Such rationalization is far easier to achieve for the brands within a company. By and large, Brewers who franchise out a brand demand that their specified process is adhered to, using their specified raw

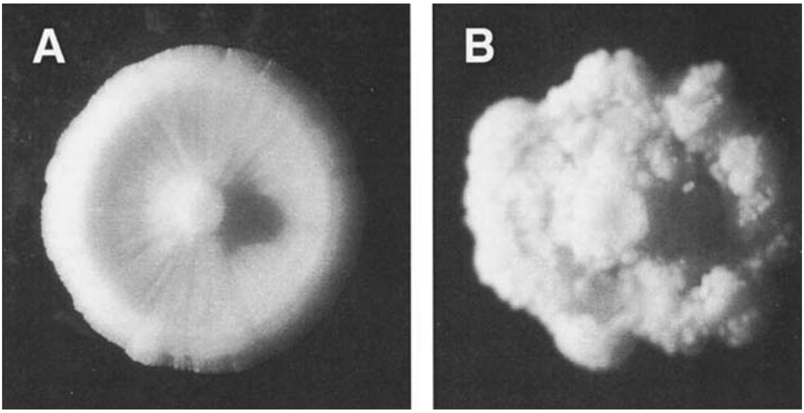


Figure 7.2 *Giant colony morphology. A is a typical lager strain and B a typical ale strain. Courtesy of Professor Graham Stewart and Dr. Inge Russell.*

materials—and that includes yeast. Basically, the greater the contribution of grist and hops to the flavor delivery of a beer, the less is likely to be the significance of the yeast strain to the character of that beer.

Identification of brewing yeast strains was once performed using a battery of physiological tests. One of the more visually compelling was the study of giant colony morphologies; the shape of the colonies developed by

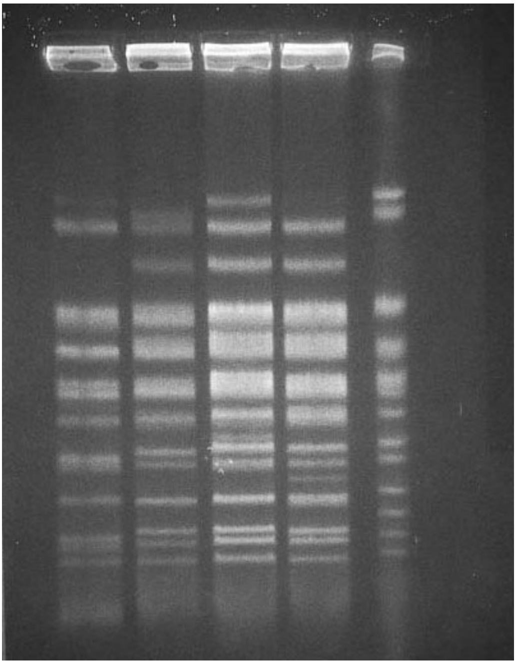


Figure 7.3 *DNA fingerprinting of yeast. This is analogous to the protein fingerprinting of barley (see caption to fig. 4.2) except that here the chromosomes of yeast have been extracted and separated by electrophoresis. Each lane represents a different yeast strain.*

growing yeast on agar plates is a characteristic of the strain (fig. 7.2). Nowadays more clinical yet perhaps more robust "typing" is achieved using DNA fingerprinting, in a technique exactly analogous to that employed in a criminal investigation (fig. 7.3). One might almost say that the "rogue" under pursuit is the yeast strain different from the one that should be being used to make the beer brand required.

The Use of Wort by Yeast

Like any other living organism, yeast needs certain essentials to enable it to grow and survive. It needs vitamins, it needs a source of nitrogen (amino acids from the breakdown of barley protein during malting and mashing), which it will use to make protein, and it needs a few trace elements. Above all else, yeast requires sugars, which it will chop up to release energy and to make smaller molecules that it will use alongside the nitrogen source to fabricate its cellular components.

Yeast can use sugars in one of two ways. If it encounters high levels of sugar, such as are found in wort, then yeast will use them by a fermentative (anaerobic) process. They are converted into ethanol and carbon dioxide, with the release of energy, as follows:

$$\underset{\text{sugar}}{C_6H_{12}O_6} \rightarrow \underset{\text{alcohol}}{2C_2H_5OH} + 2CO_2 + \text{energy}$$

However, if the sugar content is low and if oxygen is available, then the sugar is used by respiration:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{energy}$$

In fermentation, about 14 times less energy is captured for each glucose molecule broken down than is the case in respiration—but it's still enough for the needs of the yeast, because of the high availability of its sugar feedstock.

This biochemistry is the basis of differentiation between yeast operating in a brewery and yeast being produced commercially for use in baking. In the latter case it is economically desirable to produce large amounts of yeast from as little sugar as possible. Therefore yeast is grown in a so-called fed-batch process, in which the sugar source (usually molasses) is dosed in a bit at a time, so that at any given point its concentration is low and the yeast is switched on to using it by respiration. Plenty of oxygen is introduced, and the yield of yeast is high. A Brewer, on the other hand, is interested in alcohol production. Sugar concentrations, therefore, are high in wort, oxygen levels are low, and the yeast metabolizes the sugars by fermentation. Indeed, the Brewer wants very little yeast production, because the more sugar ends up in new yeast cells, the less has been converted into alcohol.

A more comprehensive equation that describes brewery fermentation would be

maltose +	amino acid →	yeast +	ethanol +	CO_2 +	energy
100 g	0.5g	5g	48.8g	46.8g	50Kcal

Even for the brewing of beer, yeast needs a little oxygen. Earlier I mentioned that the yeast membrane is important for healthy yeast. This membrane contains various components, among which are sterols and unsaturated fatty acids. Yeast uses oxygen in the synthesis of these materials. So the Brewer carefully introduces just the right amount of oxygen into wort to enable the production of the appropriate amount of membrane material. Too little, and the yeast won't ferment the wort efficiently. Too much, and yeast growth will be excessive and alcohol yield will be lowered.

Yeasts can be classified in yet another way—according to the amount of oxygen they require before they will ferment wort efficiently. Some are satisfied when the Brewer "air-saturates" the wort—bubbles air into the wort after cooling, which introduces approximately 8 ppm. Some strains are happy with half that level, while others demand oxygen saturation (16 ppm), and yet others aren't even satisfied with this amount of oxygen.

Setting Up a Brewery Fermentation

Getting the right level of oxygen into wort prior to pitching the yeast is but one of the conditions that has to be met.

First, the wort itself. It needs to have the correct strength in terms of level of sugar. Increasingly, fermentations are performed at so-called high gravity, in which case the concentration of wort (and, proportionately, of oxygen and yeast) is higher than what is needed to give the desired final alcohol content; this is to maximize fermenter capacity. At the end of the process the beer is diluted with deaerated liquor (water) to the required alcohol content.

Irrespective of whether fermentation is at high or at "sales" gravity (i.e., fermentation of wort at the strength that gives the required beer without dilution), the concentration of sugars is measured by specific gravity (which is the weight of a volume of the wort relative to the weight of the same volume of water). The units most frequently used to quote specific gravity are degrees Plato; 1° Plato equates to 1g sucrose per 100 g water. So, if wort has a specific gravity of 10° Plato, it has the same specific gravity as a 10% solution of sucrose.

The wort also needs to have the required level of solid material suspended in it. This is the so-called cold break produced in the brewhouse (see chapter 6), which is rich in lipids. Brewers differ hugely in their opinions on whether the presence of this material is a good or a bad thing. Some, for instance many German Brewers, are adamant that cold break causes only problems and that it is a serious cause of poor foams and excess staleness in beer. The opposing view is that some solids in wort are good news, because they promote a vigorous fermentation. This may be because they provide useful lipids and, perhaps, trace metals to the yeast, but is more likely to be due to the fact that the particles form nucleation sites for gas release (see chapter 3), which keeps yeast in suspension and therefore in contact with wort for fermentation, as well as preventing the accumulation of carbon dioxide that tends to inhibit yeast metabolism.

The next essential is to use the correct level of yeast, which in turn is in the proper state of health and purity. The process of adding yeast to wort is called "pitching." As a rule of thumb, 10 million yeast cells will be added per milliliter of wort at 12° P, with proportionately more added if the wort is stronger than this, or less if the wort is weaker. To measure the amount of yeast, most Brewers will count the number of cells seen under a microscope in a drop of the yeast suspension placed on a special slide that is divided into grids. This device is called a hemocytometer, because it was originally developed for counting red blood cells in clinical labs. By knowing how much suspension was put onto the slide, the Brewer can calculate the cell concentration. Some Brewers are rather more sophisticated than this and automatically dose yeast on the basis of measurements made with probes put directly into the pipeline that leads from the yeast storage tank to the fermenter. These probes work on various principles, among them are measurement of the capacitance of the yeast cells and light scatter. Suspensions of particles, such as yeast, scatter light in proportion to the number suspended per unit volume. Another method takes advantage of the fact that yeast cells can store electrical charge (i.e., they are capacitors) in proportion to how many cells are present. Dead cells and trub do not register.

The number of yeast cells added is important. So too is the health of the yeast. Dead cells won't ferment wort into beer. Just as significantly, the products of their decay can cause problems for the Brewer. The most common means for measuring the viability of yeast involves a dye called methylene blue. Living yeast is capable of decolorizing this dye, but dead cells aren't; as a result, they stain blue.

Even if a cell is living, it doesn't necessarily mean that it is in a fit state for carrying out an efficient fermentation. When yeast is in a healthy and vigorous condition, ready to do its job, it is said to have vitality. The analogy would be the average couch potato compared with a championship winning athlete. It is the latter who possesses vitality, even though both guys are living. Measurement of vitality is not a straightforward issue, and there is no agreement on the best way of assessing it. Most Brewers recognize that the most appropriate course of action is to look after their yeast, ensure that it doesn't encounter stresses such as heat shock or those that arise from leaving it in contact with beer long after fermentation is complete. By protecting the yeast they stand to keep it in good condition.

The only other ingredients likely to be included in a brewery fermentation are a "yeast food," most frequently a zinc salt, and antifoam. Zinc is a key component of one of the enzymes that yeast requires to carry out alcoholic fermentation. Other yeast foods are more complex mixtures of amino acids and vitamins, but many folk would have it that this solid addition merely acts as a nucleation site in exactly the same way as cold break.

Antifoam is required if a fermentation is characterized by high levels of head formation. This occurs particularly with certain types of yeast and for fermentations carried out at the higher end of the temperature range. Such "overfoaming" has two consequences. First, the capacity of the vessel is reduced: the Brewer is obliged to put less wort into the fermenter, otherwise it will overflow during the process. Second, any foaming during the process reduces the amount of material that will survive to support the head on the finished beer in the glass. To minimize this foaming, many brewers add antifoam agents, most frequently those based on silicone. It is essential that they are removed efficiently by adsorption onto the yeast and in the filtration operation, otherwise they will damage the head in the beer itself.

The Fermentation Cellar

Many types of fermenter exist in breweries across the world. Basically, though, they can be divided into two categories: square (fig. 7.4) and cylindroconical (fig. 7.5). The original commercial fermenters were open squares, and these are still used extensively for the production of ales in the United Kingdom. These days they are fabricated from stainless steel, but over the years they have been constructed from oak, slate, copper, and reinforced concrete. They come in a vast range of sizes, and cylindroconical vessels capable of holding over 13,000 hectoliters have been used. More commonly, "squares" are between 150 and 400 hl. Squares are highly suited to fermentations with top-fermenting yeasts; the yeast is periodically skimmed from the surface of the vessel. Clearly there is a substantial risk of contamination, and you will soon discover if you lean over such a tank and inhale that there are vast quantities of carbon dioxide evolved that will, literally, take your breath away. (Incidentally, in case the reader is worrying that the Brewer is

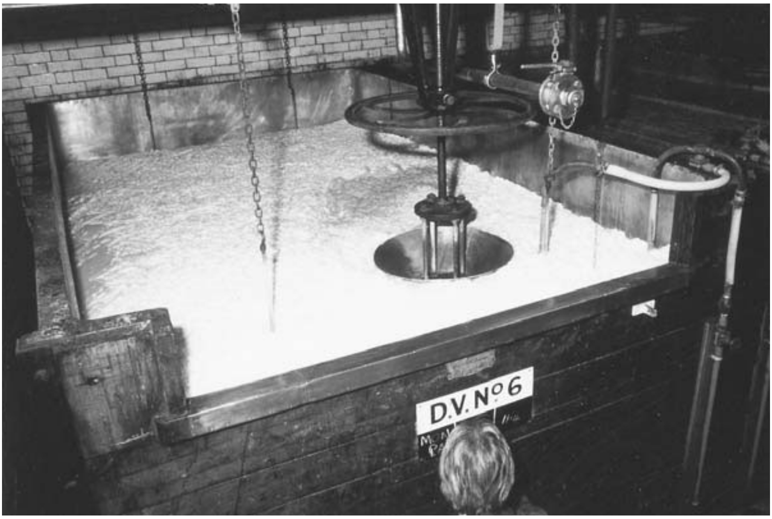


Figure 7.4 *A traditional square fermenter.*

carelessly pumping greenhouse gases into the atmosphere, it should be stressed that the amount of carbon dioxide produced by fermentation in the world's breweries is very minor when compared with the amount of this gas that you and I and the rest of the world's animal population breathe out every second of every day. Not only that, but remember that it takes a lot of carbon dioxide to support the growth of barley and hops by photosynthesis—rather more, in fact, than is produced during fermentation of beer.)

Many Brewers seek to collect the carbon dioxide from fermenters to put, for instance, into cylinders and use as a motor gas in pub dispense systems. CO_2 collection is possible from closed fermenters. Some of these vessels are little more than open squares with a lid, but for the most part fermenters these days are cylindroconical tanks, which are seldom of a capacity less than 600 hl but which routinely can be as large as 7,000 hl. Once the trend was for installation of bigger and bigger vessels; such vessels do make sense in breweries that have limited ground space and are producing large volumes of one or a very few brands. There are, however, potential problems, insofar as yeast does behave differently, depending on the hydrostatic pressure it encounters, and it may change its output of flavor materials, leading to a perceptibly different character in the beer. In particular for breweries producing a diversity of brands it makes more sense to use smaller fermenters.

Cylindroconical vessels were originally developed by Nathan around 1900 and have the advantages of better mixing due to convection currents set up by rising gas bubbles, ease of temperature control through thermostatted jackets, and easy and hygienic recovery of yeast from the base (cone).

Figure 7.5 *A schematic drawing of a cylindroconical fermentation vessel. Courtesy of Anheuser-Busch, Inc.*

These vessels are also easily cleaned using a water spray, followed by either dilute (1%) caustic or phosphoric acid and another water rinse, usually prior to a sterilant rinse with either hypochlorite or perchloric acid. These various treatments are sprayed into the empty tanks from a spray ball (nozzle). (Incidentally, such CIP is also employed at other stages through the brewery between brews to ensure cleanliness in all types of vessel and pipeline.)

It is possible to deliberately apply a pressure to these vessels during fermentation: the formation of esters, for instance, is suppressed at higher pressures.

Whichever type of fermenter is employed, the principles of what happens during the fermentation are similar. Yeast takes up sugar (and the other materials) from wort and converts it into alcohol and CO_2. Most commonly, the progress of fermentation is monitored by measuring the decline in the specific gravity of the wort (fig. 7.6). This decrease occurs because the specific gravity of a solution of ethanol is vastly lower than that of a mixture of sugars. Alongside the fall in specific gravity is a drop in pH, as yeast secretes hydrogen ions and certain organic acids (such as citric and acetic acids, the

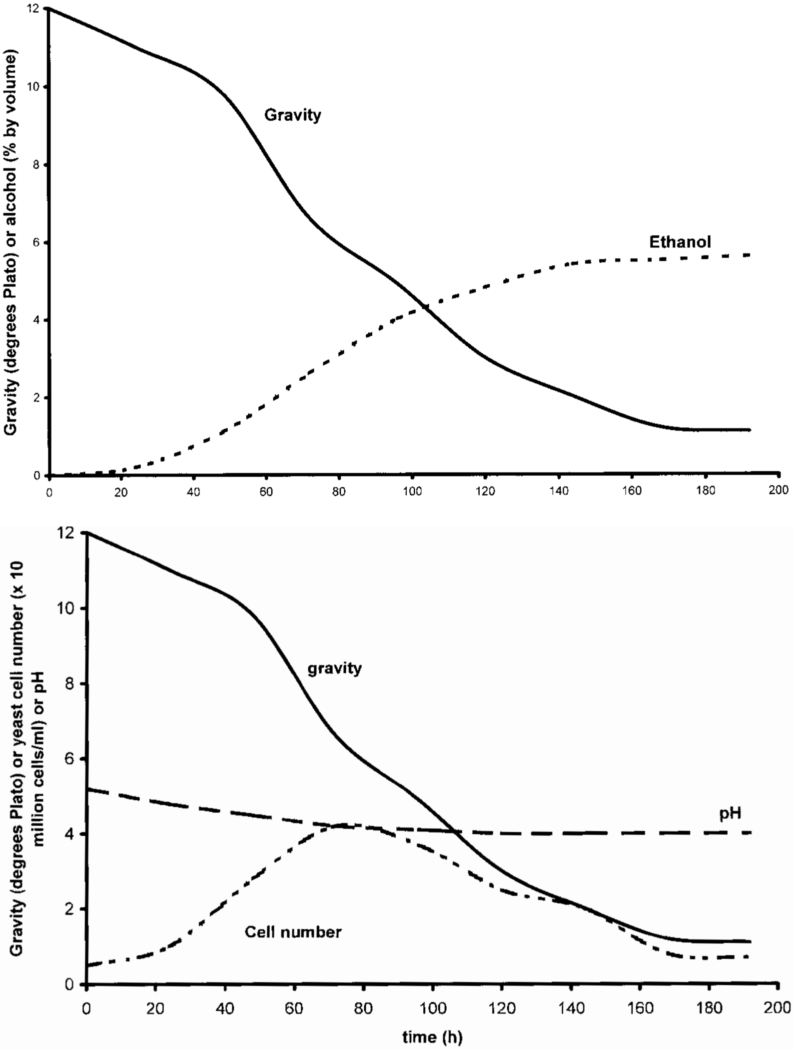


Figure 7.6 *Changes marking the progress of a fermentation. (Top) The specific gravity falls because sugars (with a much higher specific gravity than water) are converted into ethanol (which has a lower specific gravity than water). (Bottom) The number of cells in suspension increases as the yeast grows by dividing; thereafter the yeast count falls because cells flocculate and leave the body of the beer. The pH falls during fermentation.*

acids found in lemons and vinegar, respectively—happily, there is rather less of either in beer) and also digests materials from the wort that act as buffers. During the fermentation, a range of molecules leaks out from the yeast cell, among which are substances that have distinctive flavors. They include esters and higher alcohols (which collectively are sometimes referred to as fusel oils), certain sulfur-containing molecules, and a particularly noxious material called diacetyl, which has a distinct butterscotch character (see chapter 3).

Typically lagers will be fermented at temperatures between 6°C and 14°C; the chosen temperature is controlled very carefully by the Brewer. Generally speaking, the more traditional the Brewer, the lower this temperature. Clearly, rates of fermentation are slower at lower temperatures. This leads to a different balance of flavor substances released by the yeast. The traditionalists would contend that the best flavor balance is achieved if the process is painstaking—at lower temperatures. In particular it is felt that this is important for the elimination of acetaldehyde. Others insist that perfectly good beer is produced by fermentation at the higher end of this temperature range. Such differences of opinion mean that fermentation of lager can take as little time as three to four days but as long as two weeks.

Ales have always been fermented at higher temperatures (15–20°C) than lagers, with the result that they tend to contain more flavor volatiles, such as esters, than do lagers. These fermentations also tend to be faster.

The vast majority of Brewers agree that diacetyl is an undesirable substance to have in the beer. This substance leaks out of yeast during fermentation but is subsequently taken up again by the yeast at the end of fermentation. The process must be continued until the diacetyl has been lowered to below 0.01–0.1 mg per liter (the target differs between Brewers, and this depends on there being enough healthy yeast present at the end of fermentation). Some Brewers allow the temperature to rise at the end of the primary fermentation to allow this mopping-up operation to occur more rapidly. Others practice krausening, in which a charge of freshly fermenting wort with a very high count of vigorously growing yeast is added late in the fermentation/maturation to provide an abundance of cells capable of eliminating the diacetyl.

Once fermentation and diacetyl removal are complete, yeast is separated from the beer. If the two are allowed to remain in contact for too long, materials can leak from the yeast cells that can damage the beer. As we have seen, much of the yeast can be readily separated from the beer, either by skimming in the case of a top-fermenting strain working in an open square, or through the collection of a bottom yeast in the cone of a cylindroconical vessel. If any further help is required, it comes in the form of a centrifuge.

There are three possible fates for the yeast. It can go to a chilled storage tank for holding for a few days prior to pitching into another fermentation. Some Brewers collect the yeast in a press. Alternatively, it may be used immediately for pitching into another vessel: this practice is often called cone-to-cone pitching, as it involves the pumping of yeast from the cone of one vessel in which fermentation is complete, into the cone of a vessel containing fresh wort. The third option is for the yeast to be disposed of. A proportion may go off to a distiller for whisky fermentation. Some will be treated with propionic acid prior to ending up as pig slurry. The majority in the United Kingdom and Australia, though, goes off for autolysis and is made into yeast extracts, marketed as Marmite or Vegemite, that end up spread on somebody's toast. It's a taste to be acquired at a very early age—the manufacturers even advertise Marmite on a platform of "you either love it or hate it."

Storage of yeast prior to repitching is itself a process demanding great care. The yeast is kept well mixed (roused), and a little oxygen may be introduced to keep the cells ticking over. The tank is also likely to be thermostatted to 0–4°C. The yeast may also have picked up some contaminants in the fermenter, which must be got rid of. This can be achieved by washing the yeast for an hour or two in a very cold solution of phosphoric acid at pH 2.2. Healthy yeast survives this treatment quite happily, but bacteria don't.

Yeast Propagation

Some Brewers have kept the same yeast going for years and years. Some of the yeast produced in fermentation is used to pitch the next batch of wort, and so on. However, it is a fact that the yeast genome (despite the aneuploidy mentioned earlier) is not totally stable, and it is desirable to repropagate each yeast strain after every 10 to 15 batches of wort have been fermented.

Propagation is from stock yeast, which may be held in various ways but is increasingly likely to be either a deep-frozen culture or even one that has been freeze-dried. When it is time to propagate, this culture will be used to inoculate a small amount of wort (perhaps 10 ml), with growth of the yeast being in progressively increasing amounts of medium (100 ml, 1 liter, and 5 liters, until the final propagator, which may have vessels ranging in capacity from 10 to 300 hl). Rigorous conditions of sterility are essential, as is a plentiful supply of sterile wort and oxygen. The aim of propagation is to produce large quantities of yeast that is in good condition for subsequent brewery fermentations. As respiration yields far more energy than fermentation, and ethanol is not a desired product of propagation, whereas yeast biomass is, highly aerobic conditions should be maintained in a propagator. The most efficient way to grow yeast is in fed-batch mode, which the purveyors of baker's yeast have long since appreciated (as mentioned earlier).

What Yeast Excretes

Beer is, of course, a delicious and wholesome product. The fact remains, though, that it is merely the spent growth medium of a fermentation process. Beer is the way it is because of the things that yeast takes away, the substances that it excretes, and the stuff that it leaves well alone. Yeast "eats" sugars, taking away excessive sweetness while simultaneously producing its most significant excretion products, ethanol and carbon dioxide. It doesn't metabolize the proteins or the bitter compounds, although both can adsorb onto the yeast wall. And, important for the flavor of beer, yeast releases flavor compounds.

I have already mentioned diacetyl, which is extremely undesirable, with the remotely possible exception of the very occasional ale where a low level of it might have some benefit. Two categories of substance that are desirable when present in the appropriate quantity for a given beer are the higher alcohols, but more particularly their equivalent esters. The flavors associated with these esters are listed in table 3.1. The levels obtained in beer depend on fermentation conditions: levels increase at higher fermentation temperatures, if less yeast is pitched into the fermenter, and if insufficient oxygen is used. Increasing the top pressure in fermentation can suppress the tendency of esters to be produced. Of particular significance, however, is the yeast strain; some strains produce more esters than others.

Yeast secretes a range of sulfur-containing compounds into beer, including hydrogen sulfide, dimethyl sulfide, and sulfur dioxide.

Sulfur dioxide is produced by yeast from the sulfate present in wort and also from some of the sulfur-containing amino acids. While not itself as flavor-active as other sulfur compounds, sulfur dioxide can suppress the deleterious flavors caused by other compounds that can arise in beer. Notably, sulfur dioxide acts as an antioxidant and helps prevent stale flavors from developing in the product.

By and large, the other sulfur compounds present in beer are strongly flavored at extremely low levels (see table 3.2). Despite their individual pungency, if they are present at relatively low levels and in the correct balance, they contribute beneficially to the flavor of many beers, especially lagers. As for other products of yeast metabolism, there are substantial differences between yeast strains in their ability to form the various sulfur compounds. A major factor, therefore, in controlling the flavor of beer is to ensure that you use the correct yeast strain, and only when it is in good condition.

In chapter 6 I discussed dimethyl sulfide (DMS) and how its level can be controlled in wort and, therefore, beer. I said that much of the DMS is purged from wort during fermentation by the vast volumes of carbon dioxide produced by yeast. There is a complication: all brewing yeasts, to a greater or lesser extent, can *produce* DMS. Over 20 years ago, Brian Anness and I showed that they do this by converting a substance called dimethyl sulfoxide (DMSO). We found not only that the DMS precursor from malt (SMM) is broken down to DMS by heat on the malt kiln but also that some DMSO is produced; DMSO gets extracted into the wort and under certain conditions is changed into DMS by yeast. One of the most important of those conditions is fermentation temperature: if lager is produced in the traditional way at low temperatures (e.g., below 8°C) then the tendency is for yeast to produce more DMS than at higher fermentation temperatures. A research group in Belgium recently suggested that the majority of the DMS found in one outstanding brand originates from this route, and now it is broadly recognized that DMSO is indeed a major player in the DMS stakes.

The immediate precursor of ethanol, acetaldehyde, is another potent flavor compound that, if present, gives a green apple flavor to beer. Ideally it shouldn't be present, but if too much oxygen is present during fermentation then it can occur. It can also be symptomatic of the presence of spoilage organisms, in this case *Zymomonas*. Indeed, abnormal levels of other flavor constituents of beer, including some of the sulfur compounds, may also be due to infection.

Organic acids (including succinate, lactate, and acetate) are normal products of the metabolism of brewing yeast. Their secretion contributes to the characteristic drop in pH that occurs during fermentation, from over 5.0 to as low as 3.8. Finally, yeast can produce medium-chain-length fatty acids, such as octanoic and decanoic acids, which can provide flavors to beer described as "goaty" and "wet dog."

Modern Fermentations

Traditionally, fermentation was performed at "sales gravity"; in other words, the strength of the finished beer was in direct proportion to the concentration and the fermentability of the sugars in the wort. This is still the norm for many Brewers, particularly those producing smaller volumes of beer. These Brewers are more likely, too, to adhere to other traditional elements of the fermentation process, such as low temperature and fermentation at atmospheric pressure. Other Brewers, meanwhile, have considered and, in many cases, implemented procedures that will greatly enhance the productivity of their plant.

High-Gravity Fermentations

Many Brewers perform their fermentations at concentrations of wort that give alcohol yields in excess of target. Following fermentation and conditioning, the beer is diluted to the specified alcohol content by the addition of water (which must be ionically comparable to beer and deaerated to prevent oxidative damage to the beer and preferably carbonated to the level of the beer it is diluting). Thus, for a beer that might traditionally have been fermented from a wort of 10°P to give 4.5% alcohol, in high-gravity fermentations the yeast might be pitched into a 16°P wort, and the ensuing beer of 7.2% alcohol diluted 10 parts beer to 6 parts deaerated water to produce the desired final beer strength.

Commercially, 20°P appears to have been as high as anyone has used to successfully fermented high-gravity brews. Providing that sufficient fermentation and downstream facilities are available, it is apparent that high-gravity brewing presents tremendous opportunities for enhancing brewery capacity and maximizing the amount of beer produced per unit of expenditure on items such as energy. To be successful, of course, it is essential that there is the wherewithal to produce such concentrated worts, and sufficient control must be exerted to ensure that the finished beers are indistinguishable from those produced at sales gravity. High-gravity worts going to fermenter can be produced by mashing at lower water-grist ratios, restricting such worts to the concentrated flows emerging early in the wort separation stage (see chapter 6), or, most typically, by boosting the levels of fermentable sugar by adding syrups to the kettle boil. Several problems must be overcome. Hop utilization is inferior at higher wort strengths; brewhouse yields are, of course, poorer; and yeast behaves differently when confronted with extra sugar, finishing the fermentation in a less healthy condition and producing disproportionately high levels of certain flavorsome substances, notably esters, as well as releasing enzymes that damage foam. These problems are not insurmountable, and the combined use of higher yeast-pitching rates and proportionately more oxygen for the yeast to use for membrane synthesis means that large quantities of the world's beer are now produced most successfully in this way.

Accelerated Fermentations

Another way to enhance capacity would be to increase the turnover of fermenters, that is, to speed up fermentations. This can be achieved by increasing the quantity of yeast pitched into fermenter (with oxygen enhanced proportionately), maintaining yeast in contact with the wort rather than allowing it to flocculate, and elevating the temperature. In each case there is invariably an effect on flavor, which will need to be addressed, perhaps by increasing the top pressure on the fermenter if this is feasible.

Continuous Fermentation

Many industrial fermentations are performed continuously. With the solitary exception of Dominion Breweries in New Zealand, this is not the case for brewery fermentations, despite the obvious potential advantages for turnover and capacity. At times over the past 30 years various breweries have installed continuous fermentation processes, notably employing tower fermenters with upflow of the liquid stream through a heavily sedimentary yeast capable of forming a plug at the base of the vessel. By adjustment to the yeast content and the rate of wort flow, green beer could be produced in less than a day. With that solitary exception, these fermenters have since been stripped out, the main reasons given being inflexibility (most breweries produce a range of beers that demand diverse fermentation streams) and infection problems: it's bad enough having a contamination in a batch fermenter but substantially more inconvenient if the fermentation is continuous. There is also the matter of beer flavor: it is an undeniable truth that virtually any change in fermentation conditions, be it temperature, yeast concentration, or, in this case, continuous processing, leads to flavor shifts.

These problems are certainly not insurmountable, as has been proved by Dominion Breweries, which for many years has used continuous fermentation to produce some excellent beers. Indeed, there is a resurgence of interest from others in this area, including the use of so-called immobilized yeast, where the yeast is attached to a solid support and the wort is flowed past. One Dutch Brewer employs this type of process in the production of a low-alcohol beer, while others (notably in Japan) are experimenting with such fermentation systems for making full-strength beers on a boutique brewery scale. Furthermore, a Brewer in Finland employs immobilized yeast in an accelerated process for eliminating diacetyl at the end of fermentation.

Fermentation is now done, and the contemptible diacetyl destroyed, but the Brewer's job is far from over. The "green beer" that has been produced still needs to be refined in terms of its flavor and its appearance. Chapter 8 describes how that is achieved and how the beer is sent into the marketplace.

8

Refining Matters

Downstream Processing

When a beer leaves the fermenter it is not the finished article. It is highly unlikely to be sufficiently clear, or "bright," and will certainly contain substances that will come out of solution in the ensuing package. Its flavor may still require some refining. All Brewers recognize the need to attend to the "raw" or "green" beer, but they differ in their opinions about quite how intense and involved this processing needs to be.

Flavor Changes during the Aging of Beer

As mentioned in chapter 7, a rate-limiting step for moving beer onward from the fermenter is the time taken to mop up diacetyl and its precursor. Some people refer to this as "warm conditioning." Many Brewers would consider this to mark the end of the useful flavor changes they can dictate in the brewery. The traditionalists would contend that the beer still needs to be stored. There is, however, very little published data to indicate what, if any, further changes take place in the flavor of beer when it is aged in the brewery.

Some major brewing companies insist on holding lager for a prolonged period at low temperatures (decreasing from 5°C to 0°C). This process (lagering) is a leftover from prerefrigeration days, when the removal of bottom-fermenting yeast demanded that the beer be held for a long time, with chilling perhaps facilitated by blocks of ice. Traditionally, beer from an already relatively cool fermentation (<10°C) was run to a cellar at a stage when there was still about 1% fermentable sugar and sufficient yeast left in it. The yeast would consume traces of potentially destabilizing oxygen and, by fermenting the sugar, release carbon dioxide that would remain in solution to a greater extent at the lower temperatures and "naturally" carbonate the product. In this way the beer might be held at 0°C for perhaps 50 days. Yeast would settle out by the end of this time, together with protein and other material, which otherwise would "drop out" as an unsightly haze in the finished beer in the customer's glass. Adherents to this technology insist that subtle changes occur in the balance of flavor compounds in the beer, in particular the removal of undesirable notes such as acetaldehyde.

These days the technology exists to cover all these requirements for prolonged storage, including the use of clarifying agents, filters, stabilizing agents, carbonation systems, all allied to the use of refrigeration, as we will see in this chapter. This doesn't keep some major players in the brewing world from insisting on the costly process of holding beer in tank for many days. They are convinced it is right; as one of them famously remarked, "If it ain't broke, don't fix it."

The Clarification of Beer

Cold Conditioning

Two types of particle need to be removed from beer at the end of fermentation: yeast and cold break. In addition, substances that are present at this stage in solution but that will tend to form particles when beer is in the trade must also be eliminated. I'll come back to that later.

The first mechanism by which particles will separate from beer is simple gravitational pull. Most Brewers will ensure that their beer is chilled to either 0°C or, better, −1°C after it has enjoyed the degree of fermentation and maturation they deem it requires. Particles will progressively sediment at this temperature, in proportion to their size, and, furthermore, materials will be brought out of solution, substances that might otherwise emerge as unsightly haze in the packaged beer.

To facilitate the sedimentation of particles, many Brewers add isinglass finings. These are solutions of collagen derived from the swim bladders of certain species of fish from the South China Seas; the dried bladders have such colorful names as Long Saigon, Penang, and Brazil lump. Collagen has a net positive charge at the pH of beer, whereas yeast and other particulates have a net negative charge. Opposite charges attracting, the isinglass forms a complex with these particles, and the resultant large agglomerates sediment readily. Sometimes the isinglass finings are used alongside “auxiliary finings” based on silicate, as this combination is more effective than isinglass alone.

Rather less widely used, but still an integral part of the process of the world’s biggest Brewer, are wood chips. Over the years these have been mostly derived from well-seasoned beech and, individually, are a few inches wide and as much as a foot long. They therefore present a very ample surface area onto which insoluble materials can stick, including the yeast that is maturing the product.

Filtration

After a period of typically three days minimum in this “cold conditioning,” the beer is generally filtered. Diverse types of filter are available, perhaps the most common is the plate-and-frame filter, which consists of a series of plates in sequence, over each of which a cloth is hung. The beer is mixed with a filter aid—porous particles that both trap particles and prevent the system from clogging. Two major kinds of filter aid are in regular use: kieselguhr and perlite. The former consists of fossils or skeletons of primitive organisms called diatoms (fig. 8.1). These can be mined and classified to provide grades that differ in their permeability characteristics. Particles of kieselguhr contain pores into which other particles (such as those found in beer) can pass, depending on their size. Unfortunately, there are health concerns associated with kieselguhr, inhalation of its dust adversely affects the

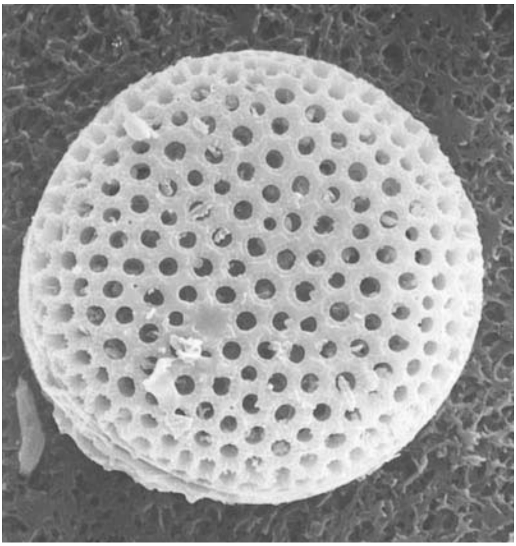


Figure 8.1 *A particle of kieselguhr as seen by electron microscopy. Magnification is two thousandfold.*

respiratory tract. Pneumatic handling systems are routinely employed to avoid such aerosols.

Perlites are derived from volcanic glasses crushed to form microscopic flat particles. They are better to handle than kieselguhr but may not be as efficient filter aids.

Filtration starts when a precoat of filter aid is applied to the filter by cycling a slurry of filter aid through the plates. This precoat is generally of quite a coarse grade, whereas the "bodyfeed" that is dosed into the beer during the filtration proper tends to be a finer grade. It is selected according to the particles within the beer that need to be removed. If a beer contains a lot of yeast but relatively few small particles, then a relatively coarse grade is best. If the converse applies, then a fine grade with smaller pores will be used.

The principles of beer filtration are similar to those I discussed when describing lautering (chapter 6). Long filtration runs depend on the conservative application of pressure and are easier to achieve if factors such as viscosity are low. As lower temperatures substantially increase viscosity and as beer should be filtered at as near 0°C as possible, it is particularly beneficial if substances like β-glucan are removed prior to this stage. Filtration can proceed until the filter is chock full of solids, either insolubles removed from the beer or the filter aid itself. For this reason, low solids in the beer and avoidance of excessive levels of filter aid are desirable, lengthening the "filter runs" before the device needs opening up, stripping down, and reestablishing.

Stabilization

Apart from filtration, various other treatments may be applied to beer downstream, all with the aim of enhancing the shelf-life of the product. There are three principal ways beer can deteriorate over time: by staling, by throwing a haze, and by becoming infected. The last of these is covered in the next section.

As shown in chapter 3, the flavor of beer changes in various ways in the package. The most significant of these changes are due to oxidation. It is now generally accepted that oxidation reactions can take place throughout the brewing process and that the tendency to stale can be built into a beer long before it is packaged and dispatched to trade. However, no Brewer would argue with the fact that the oxygen level in the beer as it is filled into its container should be as low as possible. The freshly filtered beer, which is called "bright beer," should have an oxygen content below 0.1 ppm, and many Brewers will insist on substantially lower levels than this. In part this is achieved by running the beer from the filter into a tank that has been equilibrated in carbon dioxide, or even nitrogen. The flow of beer into the vessel is gentle. And if, once the vessel is full, the oxygen content of the beer exceeds specification, then the vessel will be purged with carbon dioxide or nitrogen to drive off the surplus oxygen. Some Brewers will add antioxidants at this stage, such as sulfur dioxide or ascorbic acid (vitamin C), but they are seldom especially useful at this stage.

Brewing scientists have a long way to go before they fully understand the very complex area of beer oxidation. They understand much more about colloidal instability, the tendency of beer to throw a haze. As a result, much more robust treatments are available to ensure that beer does not go cloudy within its shelf-life.

A haze in beer can be due to various materials, but principally it is due to the crosslinking of certain proteins and certain tannins (or polyphenols) in the product. Therefore, if one or both of these materials is removed, then the shelf-life is extended.

As already mentioned in chapter 6, the brewhouse operations are in part designed to precipitate out protein-tannin complexes. Thus, if these operations are performed efficiently, much of the job of stabilization is achieved. Good, vigorous, "rolling" boils, for instance, will ensure precipitation. Before that, avoidance of the last runnings in the lautering operation will prevent excessive levels of tannin entering the wort.

We have also seen that cold conditioning also has a major role to play, by chilling out protein-polyphenol complexes, enabling them to be taken out on the filter. Control over oxygen and oxidation is just as important for colloidal stability as for flavor stability, because it is particularly the oxidized polyphenols that tend to crosslink with proteins.

For really long shelf-lives, though, and certainly if the beer is being shipped to extremes of climate, additional stabilization treatments will be necessary.

In the 1950s it was shown that nylon could efficiently remove polyphenols from beer. Nylon has rather more stylish applications in society these days, leaving an altogether more efficient if less glamorous material with the job of taking tannins out of beer: polyvinylpolypyrollidone (PVPP). This can either be dosed into tanks as a solid prior to filtration or can be impregnated into filter sheets. After use it can be regenerated by treatment with caustic soda.

Ironically, one of the foremost treatments used to eliminate haze-forming proteins from beer is to *add* more tannin, in the form of tannic acid, which is extracted from gall nuts. While this boosts polyphenol levels, this is not a concern, because the proteins that they are able to react with will be removed in the brewery. Indeed, there is a school of thought that better beers contain higher levels of polyphenol, because these molecules contribute to body and also protect against staling through their role as antioxidants. Tannic acid is added at the cold conditioning stage.

Silica hydrogels and xerogels are increasingly being used to remove haze-forming proteins from beer. These are matrices literally produced from a fundamental component of sand, but in forms that have porous structures able to absorb macromolecules such as proteins. A range of these products is available, varying in their ability to take up proteins of different sizes. Most important, it is claimed that use of these materials does not eliminate the class of proteins that contribute the foam to beer.

A third opportunity to remove haze-forming protein is to add a protein-degrading enzyme to the beer. Most commonly brewers will use papain, from the paw paw—the same enzyme that is used in meat tenderizer—but it is known that foam suffers as a result.

To reinforce beer foam, and particularly to help its resistance to the damaging effects of oils and fats (see chapter 3), some Brewers add propylene glycol alginate (PGA) to their beer. Like any material used in the brewing industry, PGA has been rigorously evaluated for its wholesomeness: like the carrageenans used in the brewhouse, it is derived from seaweed. The reader will be struck by the natural origins of the materials used in beer, not only the major raw materials but also processing aids. Apart from PGA and carrageenan, we have isinglass finings (fish), kieselguhr (skeletons of diatoms), tannic acid (gall nuts), and beech wood chips.

Removing Microorganisms

Although beer is relatively resistant to spoilage (see chapter 3), it is by no means entirely incapable of supporting the growth of microorganisms. For this reason, most beers are treated to eliminate any residual brewing yeast or infecting wild yeasts and bacteria before or during packaging. This can be achieved in one of two ways: pasteurization or filtration.

Pasteurization. This can take one of two forms in the brewery: flash pasteurization for beer prepackage, typically on its way to kegs or heat-sensitive plastic bottles, and tunnel pasteurization, for beer in can or bottle. The principle in either case, of course, is that heat kills microorganisms. The higher the temperature, the more rapidly microorganisms are destroyed. A 7°C rise in temperature leads to a ten-fold increase the rate of cell death.

In flash pasteurization, the beer flows through a heat exchanger (essentially like a wort cooler acting in reverse—see chapter 6), which raises the temperature typically to 72°C. Residence times of between 30 and 60 seconds at this temperature are sufficient to kill off virtually all microbes. Ideally, there won't be many of these to remove: good Brewers will ensure low loading of microorganisms by attention to hygiene throughout the process and making sure the previous filtration operation is efficient. The configuration of the flash pasteurizer is such that heat from the beer leaving the device is used to warm that entering. It is essential that the oxygen level of the beer is as low as possible before pasteurization, because when temperatures are high, oxygen is "cooked" into the product, giving unpleasant flavors.

Tunnel pasteurizers are large heated chambers through which filled and sealed cans or glass bottles are conveyed over a period of minutes, as opposed to the seconds employed in a flash pasteurizer. Accordingly, temperatures in a tunnel pasteurizer are lower, typically 60°C for a residence time of 10–20 minutes.

Sterile Filtration. An increasingly popular mechanism for removing microorganisms is to filter them out by passing the beer through a fine mesh filter. The rationale for selecting this procedure rather than pasteurization is as much for marketing reasons as for any technical advantage it presents: many brands of beer these days are being sold on a claim of not being heat treated and therefore free from any "cooking." In fact, provided the oxygen level is very low, modest heating of beer does not have a major impact on the flavor of many beers, although those products with relatively subtle, lighter flavor will obviously display "cooked" notes more readily than will beers that have a more complex flavor character.

The sterile filter must be located downstream from the filter that is used to separate solids from the beer. Sterile filters may be of several types, a common variant incorporating a membrane formed from polypropylene or polytetrafluoroethylene and having pores of between 0.45 and 0.8 μm.

Gas Control

Apart from stabilization downstream, final adjustment will be made to the level of gases in the beer. As already discussed, it is important that the oxygen level in the bright beer is as low as possible. Unfortunately, whenever beer is moved around and processed in a brewery, there is always the risk of oxygen pickup. For example, oxygen can enter through leaky pumps. A check on oxygen content will be made once the bright beer tank is filled, and if the level is above specification, oxygen will have to be removed. This is achieved by purging the tank with an inert gas, usually nitrogen, from a sinter in the base of the vessel. It is not a desirable practice, because whenever a purging process takes place there is a foaming of beer. The foam sticks to the side of the tank and dries, and the resulting flakes fall into the beer to form unsightly bits.

The level of carbon dioxide in a beer may need to be either increased or decreased. The majority of beers contain between 2 and 3 volumes of CO_2, whereas most brewery fermentations generate “naturally” no more than 1.2–1.7 volumes of the gas. The simplest and most usual procedure by which CO_2 is introduced is by injection as a flow of bubbles as beer is transferred from the filter to the bright beer tank. If the CO_2 content needs to be reduced, this is a more formidable challenge. It may be necessary for beers that are supposed to have relatively low carbonation (beers such as the nitrokegs or draft beers in cans discussed in chapter 2), and, just like for oxygen, this can be achieved by purging. However, concerns about “bit” production have stimulated the development of gentle membrane-based systems for gas control. Beer is flowed past membranes made from polypropylene or polytetrafluoroethylene that are water-hating and therefore don’t “wet-out.” Gases, but not liquids, will pass freely across such membranes, the rate of flux being proportional to the concentration of each individual gas and dependent also on the rate at which the beer flows past the membrane. If the CO_2 content on the other side of the membrane is lower than that in the beer, then the level of carbonation in the beer will decrease. If the CO_2 content on the other side of the membrane is higher than that in the beer, then the beer will become more highly carbonated. Gases behave independently, so the membranes can be used simultaneously to remove CO_2 from a beer and to remove any oxygen from it, providing the levels of both gases are lower on the other side of the membrane. This technique is also an excellent opportunity to introduce nitrogen into beer, a gas that, as already mentioned (chapter 3), has tremendous benefits for beer foam.

Packaging

The final process stage, prior to the warehousing of the beer, is to put it into the intended package. Table 1.2 shows the relative distribution of beer packaged for draft (“large pack”) dispense, as opposed to “small pack,” in different countries of the world. In the United States in 2000 the balance of packaging was 9% on draft, 51% into cans, 38% into nonreturnable glass bottles, and the remainder in glass bottles that are returned to the Brewer for washing and refilling. The equivalent percentages in the member states of the European Union are shown in table 8.1. As mentioned in chapter 1, Ireland and the United Kingdom sell a large proportion of their beer on draft dispense. In most other countries the favored package is the bottle, usually one that is returned to the brewery for washing and reuse. In France and Italy, though, much of the beer is retailed in nonreturnable glass, while Sweden is the country that sells the highest proportion of beer in cans. It is only very recently that pressures from the European Community have come to

Table 8.1
Domestic Beer Sales by Container Type (1999)

Country	*% draft*	*% can*	*% non-returnable bottle*	*% returnable bottle*
Austria	32	13	2	53
Belgium	39	10	2	49
Denmark	10	0	0	90
Finland	22	6	0	72
France	23	9	56	12
Germany	19	17	5	59
Greece	4	20	3	73
Ireland	78	15	3	4
Italy	17	9	63	12
Luxembourg	54	5	10	31
Netherlands	31			
Norway	26	17	0	57
Portugal	29	3	13	55
Spain	33	14	23	30
Sweden	13	60	<1	27
Switzerland	34	6	26	34
United Kingdom	62	26	11	1

Source: Brauwelt International
Note: A blank space means individual data for small-pack products are not available.

bear in Denmark, obliging them to release beer in cans. Back in North America, an obvious difference between "small-pack" beer in the United States and Canada is the heavy preponderance of nonreturnable glass in the United States, whereas in Canada the bulk of bottled beer is in returnable glass.

Time was when all beer was on draft, in that beer was purchased from the alehouse or even the brewery in earthenware and pewter jugs and diverse other receptacles. In the United Kingdom it was the removal of a tax on glass that stimulated the bottling of beer as the twentieth century dawned.

The first trials on putting beer into cans took place in post-Prohibition New Jersey, when the Kreuger Brewing Company of Newark first sold canned beer in January 1935. It was an immediate success: here was a packaging medium that was light and nonbreakable and, furthermore, that protected beer absolutely from the adverse influences of light. Just one year later the Welsh Brewer Felinfoel emulated Kreuger, taking advantage of the presence of can manufacturing capabilities with the steel industry nearby. Now canned beer accounts for a quarter of the beer production in the United Kingdom, a proportion that has increased substantially in recent years following the development of the "widget" (see chapter 2) and the shift in the direction of drinking at home. Enormous improvements in the barrier and feel properties of plastics, which mean that they are much less likely these days to permit oxygen ingress and also have a more prestigious appearance, means that there is likely to be an ongoing sizeable swing to beer in this packaging matrix. This will greatly enhance retail opportunities as well as lightweighting beer for shipment.

The traditional package for beer in the United Kingdom, of course, is the cask, originally made from wood by coopers but increasingly made of aluminum or stainless steel. There is still a healthy market for cask-conditioned ale in the United Kingdom—beer that is not pasteurized and retains yeast within it that serves to naturally carbonate the product. The yeast is settled out from the beer using isinglass finings, and it is essential that the beer be handled carefully to avoid disturbing the sediment, rendering the beer cloudy. And if it is disturbed, the sediment should be capable of resettling, perhaps several times.

Although the remarkable growth of microbrewers in the United States has reintroduced ale increasingly into the consciousness of the U.S. drinker, such products have not always achieved total acclaim among American drinkers. Certainly, the U.S. airmen stationed in East Anglia, England, in World War II didn't care to have cloudy beer delivered to them as they returned from missions, and a shortage of glass meant that bottled beer was out of the question. The quandary prompted General Curtis Le May to approach a nearby Brewer, Greens of Luton, to see how they could overcome the problem. More than $150,000 was spent on developing the process of putting beer that was carbonated and sediment-free into metal barrels. "Keg" beer was born.

Filling Bottles. Glass bottles used for holding beer come in diverse shapes and sizes. The glass may be brown or black, green, or clear (which is usually referred to as "flint" glass). Marketing people are increasingly obsessed with beer being packaged in any color of glass, as long as it isn't brown! They should listen to their technical colleagues: as noted in chapter 3, unless precautions are taken, beer develops a pronounced skunky character within seconds of exposure to light. Brown (or black) glass minimizes the access of light to beer, whereas green or flint glass provides no protection whatsoever.

Bottles entering the brewery's packaging hall are first washed, regardless of whether they are one-trip or returnable. For the former, they will receive simply a water wash, as the supplier will have been required to make sure they arrive at the plant in a clean state. Returnable bottles, after they have been automatically removed from their crate and delivered to conveyors, need a much more robust cleaning and sterilization, inside and out, involving soaking and jetting with hot caustic detergent and thorough rinsing with water. Old labels will be soaked off in the process. The cleaned and sterilized bottles pass an empty bottle inspector (EBI), a light-based detection system that spots any foreign body lurking in the bottle. Now they're on their way to the filler.

The beer coming from the bright beer tanks (i.e., after filtration) is transferred to a bowl at the heart of the filling machine. Bottle fillers are machines based on a rotary carousel principle. They have a series of filling heads: the more heads, the greater the capacity of the filler. Modern bottling halls are capable of filling more than 1,200 bottles per minute. If you go into the bottling hall you will see these mighty beasts whirling round with empty bottles chinking their way toward it and full ones whizzing away from it.

The bottles enter on a conveyor, and each is raised into position beneath the next vacant filler head, each of which comprises a filler tube. An airtight seal is made, and, in modern fillers, a specific air-evacuation stage starts the filling sequence (I have already shown how damaging oxygen is to beer quality). The bottle is counterpressured with carbon dioxide, before a valve is opened to allow the beer to flow into the bottle by gravity from the bowl. The machine will have been adjusted so that valve is open long enough to allow the correct volume of beer to be introduced. Once filled, the "top" pressure on the bottle is relieved, and the bottle is released from its filling head. It passes rapidly to the machine that will crimp on the crown cork, but en route the bottle will either be tapped or its contents "jetted" with a minuscule amount of sterile water in order to fob the contents of the bottle and drive off any air from the space between the surface of the beer and the neck (the "headspace").

Next stop is the tunnel pasteurizer (see earlier), if the beer is to be pasteurized after filling—although, as already mentioned, more and more beer is being sterile filtered and packaged into already sterilized bottles. In the latter case, the filler and capper tend to be enclosed in a sterile room to which only necessary personnel are allowed access.

The bottles now pass via a scanner, which checks that they are filled to the correct level, to the labeler, where labels are rolled onto the bottles, and then perhaps to a device that will apply foil over the cap. Other specialist equipment may involve jetting on a packaging date, or "best before" or "born on" date. Finally the bottles are picked up by a machine that places them carefully into a crate, or box, or whatever secondary package they will be transferred to the customer in. Perhaps they will go straight from this operation onto a truck or rail car for shipping, but more frequently they will be stored carefully in a warehouse prior to release.

Canning. Putting beer into cans has much in common with bottling. It is the container, of course, that is very different—and definitely one trip!

Cans may be of aluminum or stainless steel, with an internal lacquer to protect the beer from the metal surface and vice versa. They arrive in the canning hall on vast trays, all preprinted and instantly recognizable. They are inverted, washed, and sprayed prior to filling, in a manner very similar to the bottles. Once filled, the lid is fitted to the can basically by folding the two pieces of metal together to make a secure seam past which neither beer nor gas can pass. (To get an idea of this, bend the fingers on both of your hands toward the palms, then put the right hand palm downwards on top of the left hand palm up before sliding the right hand towards the right until the ends of the fingers on the right hand are tight underneath those on the left hand. Squeeze the fingers on both hands toward your palms: the tight fit you have created is exactly analogous to the seal between a can and its lid.)

Kegging. Kegs are manufactured from either aluminum or stainless steel. They are containers generally of 1 hectoliter or less, containing a central spear through which the keg is washed, filled, and emptied in the bar. Kegs, of course, are multitrip devices. On return to the brewery from an "outlet," they are washed externally before transfer to the multihead machine, whose successive heads perform their washing, sterilizing, and filling. Generally the kegs are inverted as this takes place. The cleaning involves high-pressure spraying of the entire internal surface of the vessel with water at approximately 70°C. After about 10 seconds, the keg passes to the steaming stage, the temperature reaching 105°C over a period of perhaps half a minute. Then the keg goes to the filling head, where a brief purge with carbon dioxide precedes the introduction of beer, which may take a couple of minutes. The discharged keg is weighed to ensure that it contains the correct quantity of beer and is labeled and palleted before warehousing.

Right to the last process stage, then, with the weighing of the kegs, the Brewer is conscientiously ensuring that the product is precisely right for the consumer. As shown in chapters 4–8, the Maltster and Brewer operate processes that are carefully controlled to ensure consistency. To help them achieve this, they need procedures for measuring the raw materials and the various streams and for analyzing the finished product in order that they can be satisfied that everything is in order. So far I have mentioned the sorts of measures that are, literally, taken to monitor the raw materials and the process. Now, in chapter 9, we will see how the Brewer analyzes the beer itself.

9

Measure for Measure

How Beer Is Analyzed

A former colleague of mine used to talk of his boyhood and of his father coming home from the pub.

"That was a good pint tonight," the father would announce, doubtless licking his lips. The implication was that, some evenings, it wouldn't be a good pint.

These days the production of beer is marked by strong quality control. Indeed, breweries are as aware as any industry of the merits of applying principles of quality assurance, with respect to an ethos of "right first time" and backed up by adherence to standards such as ISO 9000.

As we have seen, malting and brewing are not simple processes. They are marked by a complex blend of vegetative and mechanical stages, at any of which there is plenty of opportunity for things to go wrong. That this is seldom the case is testimony to the skill of the Maltster and the Brewer—and to the availability of robust analytical methodology.

The Analysis of Beer

A Brewer would not succeed if its measurements were made on finished beer alone. Throughout this book, I have mentioned the sorts of specifications that are made on raw materials and in individual process stages. The establishment of specifications demands the availability of methodology to make the necessary measurements. Wherever possible, Brewers seek to install sensors to enable them to make their measurements automatically, together with associated control systems that respond to the values measured and that, if values are out of specification, adjust a relevant parameter in order to push the process back on track. For example, temperature is readily measured remotely during fermentation and, if it rises, can be automatically lowered by triggering the circulation of coolant through the jackets of the fermenters.

Temperature is one of the fundamental measurements that need to be made throughout the malting and brewing processes in order that they can be controlled. Others include weights, rates of liquid flow, pressure, and fill heights in vessels. Table 9.1 lists the other parameters that are routinely checked in a brewery to confirm that the process is progressing according to plan at all stages.

This chapter concentrates on the analysis of the finished beer itself. The techniques applied are used to confirm that a batch of beer is acceptable for packaging and for subsequent release into the trade. Some of the methods will be also used in the trade to confirm that the product is in good condition. They can also be applied to assess a competitor's beers, to see what "tricks" it is employing and to try to unravel some of the procedures it is using to make a particular beer.

This said, and despite the fierce competition that exists between Brewers, they do share a spirit of cooperation with respect to establishing the methodology that will be used to measure their products. The driving forces for this are several. For instance, Brewers must clearly use methods for measuring alcohol that enable direct comparison of the strength of their various products for duty declaration purposes and for identifying for the consumer how strong a given product is. Secondly, there is much crossbrewing of beers: a Brewer may well franchise-brew the products of a competitor. There is self-evidently a need for a common "language" to describe the attributes of a beer.

For these reasons, Brewers come together through various fora. In 1886, the Laboratory Club was set up at a meeting in, of all places, a coffeehouse in Fitzroy Square, London, to act as a meeting point for British Brewers to enable them to share experiences. It developed into the Institute of Brewing (IOB), now known as the Institute and Guild of Brewing (IGB), which these days serves this purpose on an international stage. Among its roles is the publication and evolution of a set of standardized methods. Relevant methods are debated in committee, before being written up in a standardized format that is clearly understandable and in a form that should be capable of faithful pursuit in whichever laboratory uses it. The method and samples for measurement are circulated to a wide range of laboratories; they individually produce a set of data that is collated and analyzed statistically by the Commit-

Table 9.1
Minimum Analyses That Should be Made and Responded to for the Brewing Process to Be Kept under Control

Parameter	*Methodology*
Absence of taints in liquor supply	Taste it daily
Specific gravity of wort collected in brewhouse, when fermenter is filled and during fermentation	Hydrometer or "vibrating" U-tube instrumentation
Dissolved oxygen in wort before yeast dosing	Oxygen sensor
Amount of yeast "pitched"	Hemocytometer, sensors based on light scatter or capacitance
Vicinal diketones in freshly fermented beer	Spectrophotometry or gas chromatography
Alcohol content of beer for declaring duty and controlling dilution of high gravity brews	Various, including distillation, gas chromatography, or near infrared spectroscopy
Gases (CO_2, O_2, N_2) in bright beer	Specific gas sensors
Clarity of bright beer	Hazemeter
Color of bright beer	Spectrophotometer, tintometer, tristimulus colorimeter
Bitterness of bright beer	Spectrophotometer, high-performance liquid chromatography
Parameters during packaging (alcohol, gases, color, contents, integrity of seams between can and lid)	Contents by weighing; physical strip down and visual examination for seam checks
Caustic strength of CIP detergent	Titration
Flavor acceptability	Taste contents of representative samples from all packaging runs

Note: Reliable assessment of weights, volumes, and temperature is a given. Regular checks of wort, yeast, and beer by microscope should also be undertaken, to look for unwelcome microbial freeloaders.

tee, who are able to assign values that indicate how consistent the results are when a method is applied by the same analyst in a single location or between analysts in different locations. Only if these values indicate good consistency and agreement will any confidence be placed in the ability of a method to give reliable and reproducible values that can be used not only for process control but also as a basis for transactions.

Similar activities occur within the European Brewery Convention (EBC) and the American Society of Brewing Chemists (ASBC). There are clear differences between the various sets of methods—but lots of similarities, too, and measures have been taken to harmonize at least the methods of the IGB and EBC. Pressures to prevent this are largely founded in history, in that the IGB methods relate more closely to technology employed in the British Isles (and some, but not all, of Britain's old colonies!), whereas the EBC methods relate to Continental brewing techniques. As brewing companies become more international and individual brands break down national barriers, it is the country of origin of a beer that tends to dictate how it will be analyzed.

The methods can be classified in several ways. Perhaps the most useful division here is into chemical analysis, microbiological analysis, and organoleptic analysis.

Chemical Analysis

Alcohol. Perhaps the most critical measure made on beer is alcohol content. In many countries (although the United States is not one of them) duty is levied on the basis of alcohol content. In the United Kingdom, for instance, the rate of duty collection is in proportion to how much alcohol there is. As of April 1, 2000, a pint of beer containing 4% alcohol fetches duty of 27 pence (40 cents), whereas a pint of beer of 5% attracts duty of 34 pence (51 cents) per pint. And you wondered why the tendency is toward lower alcohol contents in the United Kingdom?

A Brewer in the United Kingdom needs to be able to declare the alcohol at least to within an accuracy of 0.1%. The methodology employed can vary: Her Majesty's Customs and Excise stipulate only that a method should be used that can be proven to give sufficiently precise results. Most commonly alcohol is measured by gas chromatography, but other methods may include distillation and specific alcohol sensors.

Allied to the declaration of alcohol, the Brewer must also identify for customs purposes (and also to satisfy weights and measures legislation) the volume of beer that is being produced for sale. This is generally established on a container-by-container basis by weighing the vessel, be it a keg, can, or bottle. Application of statistical distribution analysis indicates whether the inevitable spread of weights across a population of containers is within acceptable limits.

Accurate measurement of alcohol is also necessary to control the strength of beer produced by high-gravity fermentation techniques. As mentioned in chapter 7, it is common practice for fermentation to be performed in a concentrated state, with the beer being diluted just prior to packaging. This dilution is controlled on the basis of alcohol content, with deaerated water being added to bring the alcohol content down to that specified for the beer in question. In many breweries this control is carried out in-line. A sensor prior to the dilution point measures the alcohol content continuously and regulates the rate of flow of beer and water at the subsequent mixing point. The alcohol-measuring sensor may be based on one of several principles, one of the most common being near infrared spectroscopy.

Carbon Dioxide. Just as carbon dioxide is produced hand-in-hand with ethanol in fermentation, so is it a critical parameter to be specified in the finished product. The level of CO_2 is measured in the bright beer tank, most frequently using an instrument that assesses CO_2 on the basis of pressure measurement. If the gas level is too low, CO_2 is bubbled in to meet the appropriate specification. If the level is too high, carbonation can be reduced to specification either by sparging with nitrogen or by the use of hydrophobic gas control membranes (see chapter 8).

Original Extract and Residual Extract. The term "original extract" is frequently encountered. Allied to the measurement of alcohol, it is an indicator of the strength of a product. If the alcohol content of a beer is known, it is possible to calculate the quantity of fermentable sugar that must have been present in the wort prior to fermentation. This can be added to the real extract measurement (sometimes called the residual extract; it consists of nonfermented material, primarily dextrins) to obtain a value for the original extract. The real extract is determined as specific gravity using a hydrometer, pycnometer, or, more commonly these days, a gravity meter. These operate on the basis of vibrating a U-tube filled with the beer. The frequency of oscillation relates to how much material is dissolved in the sample. The real extract tells the brewer whether the balance of fermentable to nonfermentable carbohydrate in the wort was correct and whether the fermentability of the wort was too high or too low.

pH. Another indicator of fermentation performance is the pH of the beer. During fermentation, acids such as citric and acetic acid are secreted by yeast, and the pH drops. The more vigorous and extensive the fermentation, the lower the pH goes. The pH has a substantial effect on beer quality (see chapter 3), not least by its influence on flavor and its influence in suppressing microbial growth. It is measured using a pH electrode. As yet, no pH probe is robust enough for placing in-line in a brewery.

Color. All beers have their characteristic color, whether it is the paleness of lagers or the intense darkness of a stout. The most frequently used procedure for assessing color is by measurement of the absorbency of light at a wavelength of 430 nm. For the lighter products there is a reasonable correlation between this value and color—but problems may occur with darker beers. The perception of color by the human eye depends on the assessment of absorption at all wavelengths in the visible spectrum. It is no surprise, then, that a panel of expert judges could tell apart beers displaying identical absorption of light at 430 nm but that had small but significant differences in hue. The modern standard for color measurement employed in many industries is based on Tristimulus values, which basically describe color in terms of its relative lightness and darkness and its hue. As yet this does not form part of any set of standardized methods, but it surely must before long. The nearest thing to it is a technique employed by many traditionalists for a great many years, namely the comparison of the color of the beer with that of each of several discs in a device called a Lovibond tintometer.

Clarity. Another key visual stimulus in beer is its brightness or clarity. Although there are a few beers in the world that are intended to be turbid to a greater or lesser extent (the delightful Coopers Brewery in Adelaide, South Australia, offers one such example), for most beers cloudiness is undesirable. Haze is measured in beer by the assessment of light scatter by particles. Traditionally this was by shining light through the beer and measuring the amount of light scattered at an angle of 90°. The more light scattered, the greater the haze. For most beers there is good agreement between the amount of light scattered in this way and the perceived clarity of the product, but not for all. Sometimes a beer may contain extremely small particles that are not readily visible by the human eye but that scatter light strongly at 90°. The beer looks bright but the hazemeter tells a different story. This phenomenon is called "invisible haze" or "pseudo haze." It doesn't present a quality problem in the trade, but it is highly problematic for the Brewer, as it is forced to make a qualitative judgment as to whether a beer rejected instrumentally is satisfactory for release to trade after all. Nowadays there are hazemeters that read light scatter at 13° rather than at right angles, and these don't pick up invisible haze. Unfortunately they miss some of the bigger particles that are detected by 90° scatter. Accordingly, some Brewers measure light scatter at both angles—but all will ultimately look at the beer as the acid test.

Dissolved Oxygen. Even if a beer is bright when freshly packaged, it may develop haze after a greater or lesser period of time in the trade. One of the causes of this could be a high level of oxygen in the package. An even more likely problem if levels of this gas were high would be the onset of staleness in the beer. Brewers, therefore, are rigorous about excluding oxygen from the packaged beer (and, to an increasing extent, they try to exclude oxygen further and further back in the process). Reliable measurement of oxygen is essential, and this is generally carried out using an electrode on the basis of principles of electrochemistry, voltametry, or polarography. It must be carried out before any pasteurization, for the heating will "cook in" the oxygen.

Prediction of Stability. Oxygen is only one factor that will influence the physical breakdown of a beer. The most common building blocks of a beer haze are proteins and polyphenols (tannins). As yet, nobody has proved which of the proteins in beer are particularly prone to throw hazes, and until this is rectified, the only way to test the level of haze-susceptible protein is to "titrate" them out. In some quality control laboratories, samples of beer will be dosed with aliquots of either ammonium sulfate or tannic acid. The more of these agents that is needed to precipitate out protein and throw a haze, the less haze-forming protein is present. Many Brewers measure the other components of haze, the polyphenols. These can be quantified by measuring the extent of color formation when beer is reacted with ferric (iron) ions in alkaline solution. Although this measures total polyphenols, and they are not all harmful (for instance, some are likely to be antioxidants), it is a very useful means for checking whether a polyphenol adsorbent such as PVPP has done its job or whether it needs to be regenerated. Most frequently, beer stability is forecast through the use of breakdown tests. Beer may be subjected, for instance, to alternate hot and cold cycles, to try to simulate storage in a more rapid time frame.

Bitterness. Most Brewers rely here on a method introduced over 40 years ago by a famed American brewing scientist, Mort Brenner. It involves extracting the bitter iso-α-acids from beer with the solvent *iso*-octane and measuring the amount of ultraviolet light that this solution absorbs at 275 nm. The greater the absorbency, the greater the bitterness. There is much debate about the use of high-performance liquid chromatography (HPLC) for the measurement of the level of bitterness in beers, and this certainly would enable the quantitation of the individual isomers of the iso-α-acids. Technically, then, a closer measure of the actual bitterness of a beer should be obtainable.

Diacetyl. All responsible Brewers will measure the level of this compound in their beers. As mentioned in chapter 7, it is produced in all brewery fermentations, which must be prolonged until such time as the yeast has consumed it. A colorimetric method is available to measure diacetyl, but more frequently it is assessed by gas chromatography. It is important not only to measure free diacetyl, but also its immediate precursor, a substance called acetolactate. If any of the latter is left in the beer, it can break down to release diacetyl in the package, giving a most unpleasant butterscotch character to the beer. Before the gas chromatography, therefore, the beer is warmed to break down any precursor to diacetyl.

Other Flavor Compounds. Diacetyl is easily the most frequently analyzed flavor component of beer. Some Brewers will measure others as well, but for all Brewers it is through smelling and tasting the beer that they will make their key assessment of its acceptability and judge whether it can be released to trade. Latterly trials have been undertaken with so-called artificial noses, sensors that are claimed to be able to mimic the human olfactory system. They are far from ready for the job (doubtless to the satisfaction of brewers everywhere). Among the volatiles that the brewing quality control lab may be required to measure, by gas chromatography, are dimethyl sulfide and a range of esters and fusel oils. It is most likely that this will be on a survey basis, perhaps monthly, rather than brew by brew.

Foam Stability and Cling. By measuring the carbon dioxide content, the Brewer has an index of whether a beer has sufficient capability to generate a foam. This will not tell the Brewer whether the resultant foam will be stable, for which another type of analysis is necessary. This is a difficult task, and there is much debate over the best way to measure foam stability. In the United States there is reasonable acceptance of the sigma value test (see "Measurement of Beer Foam Stability") as the recommended method. The IGB does not seem to feel that any method is worthy of recommendation. The two most frequently used procedures worldwide are those of Rudin and the NIBEM.

If the measurement of head retention is challenging, then that of lacing is particularly challenging (see "Measurement of Beer Foam Lacing").

An alternative strategy for assessing the foaming potential of a beer is to measure the various components of the beer that will promote foam and ensure that they are present. Equally important, one would monitor and ensure the absence of foam-negative components. By measuring CO_2 and bitterness, the Brewer already "has a handle" on two key components that promote foam. Chromatographic, spectroscopic, and immunological methods have all been used to measure the hydrophobic polypeptides that promote foam. And those Brewers who use nitrogen gas to promote excellence in their foams can measure it using an instrument that relies on membrane separation and specific conductivity measurement. The presence of foam-negative components can be measured by assessing the ability of so-called lipid binding proteins to sequester the damaging species, thereby improving the head. However, it is far more likely that these foam inhibitors will get into the beer during the dispense and consumption of beer rather than in the brewery itself, for example from dishwashing detergents and rinse aids or from greasy food. No method for assessing foam quality can forecast all the perils that a beer must face and predict the ingress of materials that will destroy the foaming potential that the Brewer has painstakingly introduced into its beer.

Metals and Other Ions. Several inorganic ions are measured in the brewery, mostly on a survey basis. Iron and copper are very "bad news" for beer, as they promote oxidation (otherwise iron would be a useful foam stabilizer).

Measurement of Beer Foam Stability

It is one of the great truths of analytical science that if there are a lot of methods for measuring something, then none of them can be much good. There are a lot of methods for measuring foam quality—at least 20!

In the United States one of the most widely used procedures is the so-called sigma value method. In this test, foam is produced by pouring the beer into a specially designed funnel and then the stability of the foam is calculated from an equation that compares the amount of beer that has drained from the foam in a period of three to four minutes with the amount of beer that is still held in the foam itself. This method, therefore, depends on measuring the rate at which beer drains from foam: the more slowly the beer re-forms as a liquid, the more stable the foam.

Derek Rudin, 40 years ago, developed another drainage procedure that employs a long thin glass tube. A little beer is introduced into the bottom of the tube before carbon dioxide is bubbled through it to convert it all into foam, which rises up the tube. When the top of the foam hits a line marked off on the glass tube, the gas supply is switched off. The foam, of course, starts to collapse, and as it does so the beer starts to re-form at the bottom of the column. The analyst, armed with a stopwatch, measures the rate at which the beer re-forms by timing the rise of the foam-beer interface in terms of the seconds or minutes it takes to pass between two more marks on the glass tube. The longer this period of time, the more stable the foam.

A third device, this one developed by a Dutchman named Walter Klopper in the seventies and called the NIBEM method, works on a different principle. Here, the beer is poured into a glass, and a plate with needles on it is lowered into the top of the foam. These needles sense the conductivity of the foam (suffice to say that this enables the needles to differentiate the liquid in the foam from the air above the foam). As the foam collapses, the needles "lose" the conductivity signal, and they send a message to a motor that lowers the needles until the foam is contacted again. This continues as the foam collapses: clearly the more rapidly the needles lower, the less stable is the foam. The rate of lowering is flashed up as a digital readout in terms of seconds.

They are measured by atomic absorption spectroscopy, as is calcium. Liquid chromatography is used to detect the levels of a range of anions, such as chloride and sulfate.

Microbiological Analysis

A few years ago a keen young brewer was inspecting the open-square fermenters in an old-fashioned English brewery when he spotted a thick crust caked onto the inside. He scraped a lump off with his hand and marched in to see the head brewer.

Measurement of Beer Foam Lacing

Few Brewers attempt to make an objective measurement of lacing. Those that do have tried photography, light scanning of the foam coverage of the glass surface with measurement by a photocell, and light scatter. I'll mention my preferred procedure—and not only because Gordon Jackson and I devised it!

There are a couple of variants of the test, but the easiest is to pour a glass of beer in the time-honored way and then to take out the beer progressively. As we saw in chapter 3, only when foam has "aged" is it capable of lacing a glass. This takes time. If you are thirsty and consume all your beer in one gulp, then there won't be any foam left sticking to the glass! If, however, you leave a minute or two between sips from the glass, then a nice pattern of cling should form on the glass (providing the beer contains enough protein and bitter compounds and the glass is clean).

In our test, then, we take the beer out of the glass in stages that are two minutes apart to mimic this sipping (technically speaking, it would be possible to remove the beer by drinking, but that hardly allows more than a few assays). The beer is in fact siphoned off through a very narrow tube lowered into the beer, and the beer-foam interface is successively lowered to a series of marks on the side of the glass.

When all the beer has been removed, 50 ml of water is used to dissolve the foam that is sticking as "lace" to the side of this glass, and the amount of ultraviolet light that this solution absorbs at 230 nm is measured in a spectrophotometer. The more ultraviolet light is absorbed, the more foam is dissolved in the water, and the greater was the lacing on the side of the glass.

It's a robust—and fun—method. Sadly, most Brewers like their quality control methods to be a tad faster than this one! More important, this method suffers from the same shortcoming as the vast majority of other methods advanced for the study of foaming: the results are inherently dependent on how the foam is generated. Factors such as the depth of the foam and bubble size can have a major bearing on the results.

"What's that, lad?" said the old man.

"It's dirt from the top of a fermenter," replied the young fellow, proud of his discovery and firmly resolved to clean up the plant.

"Well, put it back," stormed the boss. "Where do you think the character comes from in our beer?"

The story is apocryphal (I think). It does, however, serve to remind us that, despite the fact that beer is relatively resistant to microbial infection, thanks to hops (see chapter 5), ethanol, low pH, high CO_2, and lack of oxygen, there is still plenty of opportunity for organisms to infect the process and the product.

Traditionally, microbiological analysis in breweries consisted of taking samples throughout the process and inoculating them on agar-solidified growth media of various types designed to grow up specific categories of bacteria or "wild yeasts" (i.e., any yeast other than the one used to brew the beer in question). When the plates were incubated for three to seven days, any bugs on them would grow to produce colonies: the more colonies, the greater the contamination. The problem is that by the time the results were made available and discussed with the Brewer, that particular batch of wort or beer would have long since moved on to the next stage. Any remedial procedures would only help subsequent brews.

Far-sighted Brewers now use a quality assurance approach to plant hygiene, allied to the use of rapid microbiological methodology. Much more attention is given to plant design for easy cleanability, checking of the efficiency of CIP systems (e.g., caustic checks), confirming that the pasteurizer is working by testing temperature, applying various checks to test that heat-sensitive components are being destroyed, and so on.

Various rapid microbiological techniques have been advocated. The most publicized and most widely used is based on "ATP bioluminescence" (fig. 9.1). The method depends on the firefly, an insect that emits light from its tail as a mating signal; this reaction is caused by an enzyme called luciferase, which converts the chemical energy store found in all organisms (Adenosine triphosphate, or ATP) to light. The enzyme can be extracted and this reaction carried out in a test tube. The more ATP is present, the more light is produced, and it can be measured using a luminometer.

The rapid test used by Brewers requires that a swab be scraped across the surface that needs to be tested. The end of the swab is then broken off into a tube that contains an extractant, together with the luciferase, and after a period that can be as short as a few minutes, the amount of light emitted is measured. The dirtier the surface (i.e., the more bugs and debris on it), the more ATP will have gotten onto the swab and, in turn, the more light will be measured. And so, in real time, an indication can be obtained of the state of hygiene of the plant. The method has been extended to measuring very low levels of microorganisms in beer, enabling the Brewer to release beer to trade with confidence just a few hours (or, at most, days) after it is packaged.

Figure 9.1 *The principle of ATP bioluminescence as a method for detecting soil and microorganisms in a brewery. Swabs used to sample different parts of the brewery are broken off in a solution containing luciferin (a substrate), a little magnesium, and luciferase, an enzyme extracted from the tail of the firefly. If there are organisms or there is soil on the swab, the ATP therein reacts with the luciferin in the presence of luciferase to produce light.*

D-Luciferin/Luciferase + ATP + Oxygen + Mg^{2+} $\longrightarrow$ 

Sensory (Organoleptic) Analysis

Although the drinking of beer is a complex sensory experience, bringing into play diverse visual stimuli and environmental factors (see chapter 3), ultimately it is the smell and taste of a product that will decide whether or not it will prove acceptable to the consumer. For this reason much time and effort is devoted within the brewery to the tasting of beer at all stages in its production.

One of my past jobs was as the quality assurance manager of a large English brewery, where the first job at break of day was to stand alongside Neil Talbot, the head brewer, and taste samples from the previous 24 hours' production. (This is not quite so delightful as it might sound, believe me.) A sip of each beer would be taken and "scored" on a scale of 1 to 4. A value of 1 indicated that the beer was of the expected high quality; 2 meant a minor flaw that would warrant a quick check of the records, but the beer could go to trade, as any deficiency was predicted to be imperceptible "in the trade"; 3 indicated a serious shortcoming in the product that demanded serious investigation and a holding of the beer while a decision was made about what to do with it; while 4 meant there was a major problem, the beer would have to be destroyed, and an urgent inquiry would have to be launched. Happily I don't recall any scores of 4, and there were very, very few 3's. We tasted beer at the cold conditioning stage, at the post-filtration stage, and after packaging. We also checked the water that was to be used to brew beer and dilute high-gravity beer.

The system was straightforward and highly effective as a screen to ensure that the highest quality standards were being maintained and that we found out as early as possible in the process if things were going awry. For instance, by tasting beer before packaging we could "nip in the bud" any faults before the expensive packaging process was carried out. The procedure demanded, of course, that Neil and I were sensitive to the flavors expected in each product. As a quality assurance technique it served the purpose for which it was intended.

Taste, though, is a complex sensation, which depends on the interaction of beer components with many receptors in the mouth and on the no less complex aroma perception through the nasal system. Sweet, sour, salt, and bitter are the basic tastes contributed by any foodstuff, and there are receptors for each on the tongue. There are, however, many other flavors in a product such as beer—they are all detected ultimately by receptors within the nose, despite the perception that they are tasted.

Because of this complexity it is not surprising that drinkers differ considerably in their sensitivity to different flavors. People can be "blind" to certain characteristics or acutely sensitive to others. In either instance it can be a problem. It's just as well that Neil and I seemed to be fairly "middle ground." If we had been incapable of spotting diacetyl, then we could have released to trade beer that most people would have deemed undrinkable. Equally, if either of us had been acutely sensitive to a given character (and I must admit to being just that with the butterscotch note from diacetyl; see chapter 7), then we might have rejected beers that the vast majority of the population would have judged perfectly acceptable.

For this type of reason, beer tasting can be much more sophisticated than simply having a head brewer and quality assurance manager standing around a spittoon (not that we ever spit it out, because [1] it was too good; [2] there is no snob value in doing so; [3] what a waste!). It is essential that reliable and statistically well-founded tests are available that can provide authoritative and semiquantitative information that can be applied to make decisions about beer quality. Broadly, these methods can be divided into difference tests and descriptive tests.

Difference Tests. As the name suggests, these are intended to tell whether a difference can be perceived between two beers. For instance, the Brewer may be interested in checking whether one batch of beer differs from the previous production run of the same beer, or whether a process change has had an effect on the product, or whether batches of the same brand of beer brewed in two different breweries are similar, and so on.

It is essential that the tasters are not distracted in this task. The environment has to be quiet, and they must not be influenced by the appearance of the product, so the beer is served in dark glasses and in a room fitted with artificial red light, with no opportunity for them to make contact with other assessors. It is important that the sensitivity of the tasters is not influenced by their having recently enjoyed a cigarette or a coffee or partaken of any strongly flavored food: it's best to have the tasting session prior to lunch, especially if curry is on the menu.

The classic difference procedure is the three-glass test: a minimum of seven assessors are presented with three glasses. Two of the glasses contain one beer, the third the other beer. The order of presentation is randomized. All the taster has to do is indicate which beer he thinks is different. Statistical analysis will reveal whether a significant number of tasters are able to discern a difference between the beers and, therefore, whether, according to the law of averages, the two beers will or will not be perceived as tasting different by the public.

Descriptive Tests. The three-glass test can be carried out essentially by anyone. However, if a Brewer wants to have specific descriptive information about a beer, then it must use trained tasters, people who are painstakingly

Table 9.2
Terms Used in the Profiling of Beer Flavor

Term from "flavor wheel"[a]	*Synonyms*
alcohol	ethanol, vinous, full
astringent	mouthpuckering, harsh, tart
bitter	tonic water, quinine
body	full: cloying, thick, chewy, creamy, viscous
	thin: watery, characterless, dull, bland
burnt	smoky, chocolate, liquorice
carbonation	high: gassy, CO_2, tingle, liveliness
	low: flat, dull, lifeless
cardboard	bready, papery, straw, sawdust
cheesy	sweaty
cooked vegetable	cabbage, parsnip
diacetyl	butterscotch, buttery, toffee, vanilla
DMS	tomato juice, black currants, canned corn, canned tomatoes, parsnip, crab
estery	banana, pear, pineapple, solvent, wine-like
fatty acid	tallowy, waxy
floral	roses, hyacinth, fresh hops, flowers
fruity	citrus, grapefruit, orange, lime
grainy	husky, mealy, corn, grits
grassy	green bean, mown grass, herbal
hoppy	resinous, fresh hops, herbal
lightstruck	skunk, leek
malty	bran, nutty, Horlicks
medicinal	TCP, disinfectant
metallic	mouthcoating, rusty, tinny
musty	moldy, earthy
phenolic	hospital, disinfectant
rancid	vomit
ribes	tomcat, catty, black currant buds
soapy	oily, goaty
sour	lemon juice
spicy	cinnamon, cloves
sulfidic	rotten eggs
sulfitic	choking, struck match
sweet	honey, syrupy, primings, cloying
toffee	black treacle, cooked sugar, caramel
worty	coconut, almond, sweet, chewy
yeasty	autolyzed yeast, yeast pressings

[a]The flavor wheel (American Society of Brewing Chemists) comprises agreed terms to describe components of beer flavor laid out as the "spokes" in a circular configuration.

taught to recognize a wide diversity of flavors, to be articulate about them, and to be able to "profile" a beer.

The terminology that is used is usually of the type illustrated in table 9.2. A group of individuals will collect around a table and taste a selection of beers, scoring the individual attributes, perhaps on a scale from 0 (character not detectable) to 10 (character intense). Obviously it takes real ability to be able to separate out the various terms and recognize them individually and without one parameter influencing another. Once the scoring is complete, the individuals will discuss what they have found and agree on how the flavor of a beer should be summarized. The findings may be reported in the form of a spider diagram (fig. 9.2).

This type of test is widely used to support new product development and brand improvement and, of course, to characterize the beers from a competitor. Once again, there are variants of it, such as the trueness-to-type test. The latter procedure is well suited to assessing whether a beer brewed in one brewery is or is not similar to the reference (standard) beer brewed in an-

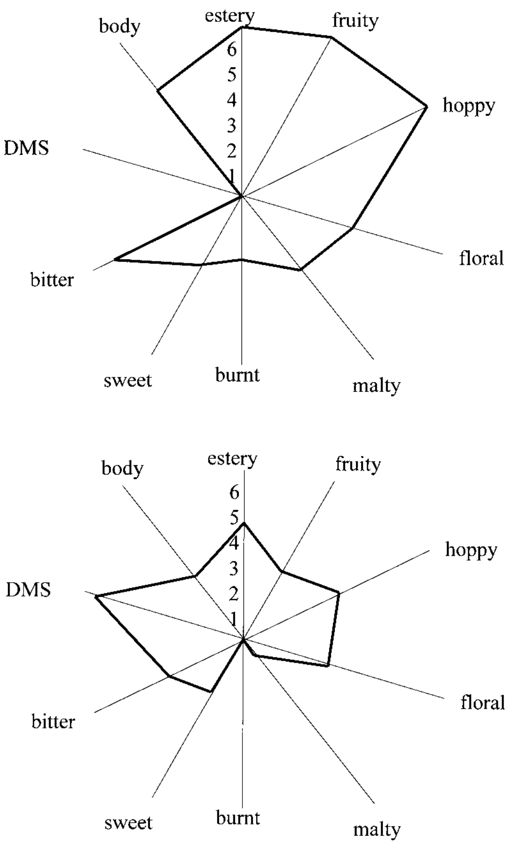


Figure 9.2 *The flavor of beer represented by "spider diagrams." Each flavor term is represented by a "spindle." The more intense the score for a term, the higher the score along the line. The individual scores are linked together to get a picture whose shape is characteristic for a product. Subsequent batches of that beer should have a pattern that essentially overlays that for the reference sample: if it doesn't, then the specific flavor defect can be identified. Comparison of the two samples illustrated in this diagram shows that the ale (top) generally has much higher flavor scores than the lager (bottom); i.e., its flavor is more complex and intense for these particular flavor notes—with the notable exception of DMS.*

other location. For each of various terms found in the flavor profile form, each assessor is asked to mark whether the sample has the same degree of that character (score = 0), slightly more (+1), substantially more (+2), slightly less (-1), or substantially less (-2). Obviously the more flavor notes that are judged to have a score of zero, the more similar are the two beers.

Another test applied by Brewers is the evening "drinkability" or "session" test. This is designed to assess whether a beer will prove satiating or whether the consumer will want to drink more than a single glass of it. One variant involves presenting the tasters (who don't necessarily have to be trained) with two or three different beers whose drinkability is under assessment. The drinkers are asked to sip-test each of them, pass comment on them, and then select one for continued drinking. They are able to switch to another beer at will. A careful record is made of how much of each beer is consumed—the highest volume indicates greatest drinkability—and the drinkers are sent home by cab.

Such a test is, of course, somewhat primitive and unsophisticated, even if it can be rather informative and, let's be honest, fun. Many Brewers would value a straightforward test that will tell them in an uncomplicated way: Will the drinker like this beer? Alas, such a test must lie a good way into the future.

Which brings me now to ask: what does the future have in store for beer and brewing?

10

To the Future

Malting and Brewing in Years to Come

The fundamental shape of the malting and brewing processes has remained similar for many years. The reader should not conclude from this that the industries are stagnant or primitive: rather, one should appreciate that the basic route from barley to beer, aided by hops and yeast, is essentially well fitted to the purposes for which it is intended. I hope, too, that the previous chapters will have led the reader to conclude that the science of malting and brewing is well understood, allowing ever tighter control of these processes.

I do not foresee a dramatic change in the unit processes of malting and brewing in the foreseeable future. Basically this is for two reasons: first, the nature of beer is as it is *because* of these processes: its flavor, its foam, its texture, its color, its wholesomeness are all dependent on the care and devotion invested by the Maltster, the Brewer, and the suppliers of hops and other ingredients. Which leads me to the second justification for leaving the basic procedures as they are: Brewers *care,* they take a pride in their products and in their heritage, and they are fundamentally convinced that the best interests of the consumer are served by ensuring that they adhere to professional standards. *Of course* the Maltster and the Brewer expect to operate efficient processes, using raw material and plant capacity resources economically. They know only too well, however, that their beers have the character they do because of a vast myriad of chemical and biochemical changes that occur during malting, brewing, fermentation, and downstream processing. It is a high-risk undertaking to mess around with them. Accordingly, the farsighted Maltster or Brewer will listen attentively to suggestions for process adjustment and will apply the science conscientiously but will resist absolutely any development that jeopardizes their product.

This book is filled with examples of how the malting and brewing processes have developed, and have become vastly more efficient, without fundamentally modifying the basic route from barley to beer. In chapter 4 we showed that interrupted steeping enabled the malting process to be foreshortened by several days and how the addition of extra gibberellic acid, a molecule naturally found in barley, can further speed up the process (if it is used; it isn't in the United States). Chapter 5 showed that the essential bitter and aroma ingredients of hops can be introduced more efficiently into the process in a form free from the vegetative parts of the plant. Chapters 6 and 7 showed how the brewhouse and fermentation operations have been subtly altered to enormously improve efficiencies, but without inherently changing the character of wort or beer: developments have included high-gravity brewing, pure yeast technology, diacetyl control, and enhanced yeast-handling strategies. Chapter 8 showed how enormous attention has been paid to stabilizing beer, with beneficial effects on the consistency of beer quality: advances here have included sterile filtration, the use of nitrogen gas, and the application of stabilizing agents such as PVPP and silica hydrogels to allow more rapid turnaround times, if that is the Brewer's desire. Finally, in chapter 9, I explored how developments in analytical techniques are being applied by Brewers to achieve tight control over their process and product, with genuine benefits for the consumer.

The future will see more of these improvements in the processes occurring. Perhaps the most publicized opportunity centers on the use of gene technology.

Gene Technology

As I write, no Maltster or Brewer is deliberately using genetically modified raw materials. The question is: will Maltsters and Brewers take advantage of this exciting new technology? I believe the answer is *yes*, but *only* once they are absolutely convinced that there are real merits in so doing.

We have seen clear evidence of the readiness of these industries to embrace new technology, but Maltsters and Brewers also apply absolute caution whenever change is suggested: only when justification is 100% will a move be made. One has only to survey the history of brewing science to realize the truth of this statement. It is now over 25 years since the first research on genetic modification of brewing yeasts took place, and plenty of yeasts have been successfully modified. As yet, *none* of them is in commercial use.

Only one genetically modified brewing yeast has been cleared through all the necessary authorities—this in the United Kingdom. Should a brewing company wish to use it, it may. As yet, none has taken up the option. In part this seems to be because no Brewer wishes to be first into the marketplace with a beer labeled "product of gene technology." More important, however, none seems to be convinced that the merits of this particular organism outweigh the very real concerns that exist with the application of this science. The first Brewer to employ genetically modified yeast will do so because it brings genuine benefit to the consumer. Perhaps the yeast will boost the levels of some component of beer that is beneficial to health (see chapter 3). Or it might be a yeast that enables beer to be brewed substantially more cheaply (although I fail to see how the science of genetic modification can hope to address one of the most crippling cost components of beer in many countries: excise duty).

The one yeast so far cleared for commercial use was "constructed" by one of my former research teams, led by John Hammond and his colleagues. Into a lager strain was introduced a gene from another yeast, this gene "coding" for an enzyme that will convert more of the starch into fermentable sugar, thereby enabling more alcohol to be made per unit of malt or, alternatively, enable less malt to be used per unit of alcohol. As mentioned in chapter 6, not all of the starch from barley is converted into fermentable sugars in conventional brewhouse operations. To produce the so-called diet beers that have more (even all) of these partial degradation products of starch (dextrins) shifted into alcohol, Brewers add an enzyme (called glucoamylase) that is capable of performing the extra conversion. What we did was to take the bit of the genetic code from *Saccharomyces diastaticus* that codes for this enzyme and transfer it to a "conventional" bottom-fermenting strain of *Saccharomyces cerevisiae.* This was done so efficiently that the extra DNA stayed in the yeast from generation to generation. Most important, we had transferred DNA from an organism that was extremely similar to the host organism: from one yeast to another one. And it worked. The host yeast was able to make the enzyme from the "foreign" bit of DNA and spew it into the wort, and there it chopped up the dextrins. The fermentations were performed on scales as large 100 hectoliters, and the beer produced was indistinguishable from that produced conventionally. The beer was produced, bottled, and labeled "for research purposes only."

The genetically modified yeast employed in making this beer, which was called Nutfield Lyte, was used as a test case for the purposes of seeking approval from the necessary U.K. authorities. For approval to be granted, the yeast had to be cleared by *four* committees: the Advisory Committee for Novel Foods and Processes within the government's Ministry of Agriculture, Fisheries, and Food; the Advisory Committee on Genetic Modification (part of the government's Health and Safety Executive); the Advisory Committee on Releases to the Environment (Department of the Environment); and the Food Advisory Committee. Four different departments had a say—four separate bodies to scrutinize every facet of the science, ethics, and safety of the project, each of whom had to be satisfied before permission was granted. And still this yeast remains in the freezer awaiting application. Everybody is applying understandable caution, but all the evidence is that the technology is sound and safe, provided that a responsible attitude is adopted.

This is certainly the case for Brewers, and for Maltsters, too, although there is some distance to go yet before suitable genetically modified barleys become available. They *will* be developed—with "new" properties, such as enhanced disease resistance, enabling a reduced need for spraying with pesticides. The Maltster will adopt the same cautious approach as the Brewer on whether to use them. Of course, both the Maltster *and* the Brewer have a stake in the use of barley: indeed, ultimately, it will be the Brewer who will drive the use (or not) of genetically modified barley.

Gene technology, then, is an exciting concept and one that could provide genuine benefits. All the signs from the brewing industry are that the technology will only be used if those benefits accrue to the consumer.

What Will the Industry Look Like in 10 Years?

So how will our beer be made in the future? Can we anticipate a radically different approach to the traditional and semitraditional processes that have been used to make the world's favorite beverage for thousands of years? Or will the basic shape of the business stay as it is, with incremental improvements rather than radical alternatives continuing as the status quo?

Some while ago I canvassed a selection of other international experts within the malting and brewing industries, asking them how they saw matters unfolding over a 10-year time frame. Their (and my own) views can be distilled as follows.

Raw Materials. Nobody envisages a dramatic shift in the grist materials that will be used for brewing. Indeed a number of Brewers have shifted back from sizable use of adjuncts to grists that are largely (if not entirely) of premium malted barley. They are convinced that this offers genuine quality, though a clear justification remains for using other cereals where they offer unique attributes to a product, in terms of flavor or color, for instance.

Figure 10.1 shows that the contribution of malt and adjuncts to the cost of beer is relatively low. There really is little strategic or financial justification for taking shortcuts with them, unless they are not available (e.g., the ban-

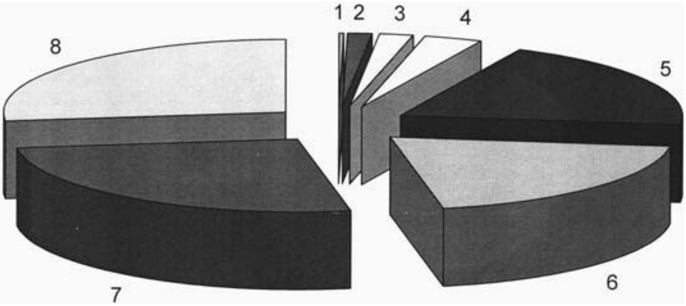


Figure 10.1 *The relative cost of producing beer: (1) hops; (2) adjuncts; (3) minor ingredients; (4) malt; (5) production; (6) sales and marketing; (7) packaging; (8) tax. This is likely to vary considerably between countries—for example, on the basis of taxation (see chapter 1). However, it is invariably the case that the cost of packaging and packaging materials, of processing (that is, the cost of people's labor, primarily), and of marketing and sales are the major element.*

ning of malt imports in Nigeria) or there is a further financial incentive so to do. Such a case arose in Japan, with taxation legislation that led to disproportionately less duty on "sparkling malt drinks," otherwise known as happoshu. They must contain less than 25% malt. They are packaged like beers and, to the consumer, are clearly from the same stable, even if the label cannot use the word "beer." Figure 10.1 illustrates that savings on a tax bill will be much more significant than savings on the grist bill. Flavors of happoshu products are pretty reasonable, if to this observer not so agreeable as high-malt brews. It should be noted that the Japanese Brewers have not strayed from their traditional high-malt recipes for their flagship products.

It is generally believed that pressures imposed by brewers seeking "clean labeling" will continue to minimize the use of additives in the growing of barley and its subsequent malting, yet everyone realizes that these agents can offer real advantages to the process and product: better to use a pesticide in the production of barley and to ensure its removal during steeping than to run the risk of a fungal infection of grain. Here, too, may be a major role for genetic modification: the construction of barleys that have in-built resistance to attack by undesirables.

There is concern that not enough premium malting-quality barley will be available to meet the increasing demand for it. Leading hop varieties, particularly those with good aroma characteristics, will continue to be in heavy demand, and there may be shortages. The shortage may be exacerbated if hop growers succeed in their quest for alternative uses for hops, for example, if of a high-value phytonutrient or two are identified, the market value of hops would skyrocket.

Brewing. The crystal ball suggests that brewhouse operations 10 years hence will not be radically different from those in place today. Already there has been an increase in the number of breweries incorporating mash filters rather than lauter tuns (see chapter 6), and no successor to the mash filter seems to be emerging. Perhaps brewhouse operations will become continuous, to match continuous fermentation operations, yet few if any Brewers seem to be convinced that continuous production of beer would be right for them.

Without doubt, though, Brewers, just like any other industrial sector, seek to lower their cost base. They all share the opinion, for instance, that processes will become far more automated, taking advantage of the rapid developments that are being made in the miniaturization, sensitivity, and flexibility of information technology. Automation has already happened to a degree, and substantial "de-manning" has occurred over the years. The most impressive example of automation I have seen was in the warehouse operations of a major Japanese brewery. All but one of the fork-lift trucks was a robot, each busily shifting beer around the site according to a program. And each truck played a tune as it trundled along—one was whistling "Yankee Doodle"!

Packaging. One brewer suggested to me that brewing could evolve into being a service to a distributed packaging industry, in the same way that the soft drink industry operates today. In other words beer would be brewed centrally and then shipped, probably in a concentrated form, to regional centers for make up to the finished product prior to packaging. It is certainly the case that the bulk of the raw materials cost, approximately half of the cost of processing and, indeed, much of the innovation, is at this stage in the brewery operation. Therefore, issues such as reduced raw materials costs (for instance, use of aluminum), recycling, de-manning of what tends to be a very labor-intensive function, and energy conservation are all to the fore, as, of course, is the journey toward plastic instead of glass bottles.

The Product. The common theme, however, which ran all through the survey replies, on raw materials, brewing, and packaging and on consideration of the beer itself, was *quality.* In particular, Brewers anticipate beers having extended shelf-lives to meet longer distribution chains, and there will be much more choice. The consumer is becoming more enlightened about issues of wholesomeness and quality: Brewers appreciate that they will have to meet drinker demand in this area, including the development of new beers with unique properties based on variables such as flavor, foaming, texture, and, in a very responsible manner, health attributes.

Research into so-called consumer sciences is developing fast. In the future, it will be possible for producers of all types of foodstuffs, including beer, to be able to forecast with much more confidence which products will be enjoyed by the customer. Understanding of the specific effects that different components of beer have on the sensory apparatus in the mouth and nose will enable the beers to be "designed" that are best suited to the enjoyment of the consumer.

Inputs and Outputs. Brewers will continue to strive toward minimizing inputs; for example, they will continue to develop their processes toward less energy demand and less water. Consumption figures for efficient and inefficient breweries, respectively, are shown in table 10.1. Many Breweries have headway to make to catch up with the pack. Even the leaders in the efficiency stakes are eager to improve.

The really energy-demanding operations in malting and brewing are malt kilning and wort boiling, and there is still some way to go in making substantial savings here without jeopardizing product quality. Developments focus on heat recovery, of course. The cost of refrigeration is also a major factor, hence the interest of a number of Brewers in lessening chilling demands.

There is some concern regarding the ongoing availability of good-quality water for malting and brewing, forcing yet more attention to reducing water consumption in cleaning operations and to the need for more recycling. Concerning outputs (other than the beer itself, of course), Brewers are adjusting their processing to reduce wastes such as spent grains, surplus yeast and, of course, waste water. Naturally, the more efficiently a material such as malt is converted into beer, the less overflow there will be to spent grains. There is a long, long way to go, though, before malt will be entirely convertible into wort and thence beer. The furthest anyone has got within the remit of a conventional brewing operation was my own previous organization (Brewing Research International), on a pilot scale, using the acid hydrolysis of the surplus grains to produce more sugars. The problem became one of "spent spent grains": the husk of barley is pretty resilient! Huskless varieties of barley are available, though they are susceptible to infection in the field and are difficult to malt because the naked grains tend to stick to one another. In terms of saving water, the focus has to be on the amount re-

Table 10.1
Inputs for the Production of 100 Hectoliters of Beer

Input	*Efficient brewery*	*Less efficient brewery*
Malt	1.5 tons	1.8 tons
Water	500 hectoliters	2,000 hectoliters
Energy	15 gigajoules	35 gigajoules
Electricity	1000 kilowatt hours	2000 kilowatt hours

quired for washing and cleaning purposes. Naturally, the smaller the plant relative to the output of beer, the less cleaning water is needed. Indeed, continuous processes run for days or weeks, potentially years, without stripping-down and cleaning and are therefore very economical in terms of water usage.

A former colleague was fond of drawing attention to the apparent illogicality of the malting and brewing processes: "We take moist barley from the field and, in drying, heat it to *drive off* water. Then we *add* water in steeping, germinate, and then *drive off* water in kilning. To the brewery—and we *add* water in mashing. Then we *drive off* water in boiling. . . ." I took the point, of course, but reminded him that all of these stages are performed for very good reasons, which is not to say that there may not be radical alternatives in the future.

Some people point out that a goodly proportion of the dry weight of a barley kernel never finds its way into a beer. What a waste! they say. They forget that good efficient modification of the endosperm requires embryo growth—it's the price to be paid. Okay, then, comes the reply, use raw barley and tip in the enzymes from a bucket. Possible—indeed, it has been done—but the flavor is *not* as good and, anyway, the extra cost of processing in the brewery (e.g., shorter filter runs) takes away much if not all of the financial benefit. Not to be deterred, the revolutionist shifts to an argument for taking the cheapest alcohol source one can find on the spot market and tipping in the flavor, color, and foam from a bottle. Sure, you can do it—but is it beer? And what will you do with all the surplus mash tuns, lauters, kettles, whirlpools, fermenters, and sundry other items? I have no difficulty with the research being put in place to do this—but for me it's a technology that will only really have its zenith on board interstellar craft headed on centuries-long journeys into outer space—and long after we traditionalists have departed this mortal coil! Beer is increasingly marketed on a platform of care, tradition, and benefit. That ought to mean that we don't stray too far from the present way of doing things (which has only truly been tweaked in relative terms over many generations) unless other substantive pressures come to bear. The fact that Brewers spend over $2.50 per barrel on advertising as opposed to just a few cents on scientific research ought to give the reader a reasonable grasp of what is generally considered to sell beer.

The Industry. There will be an ongoing drive toward international brands—recognized names thriving far beyond home base. This will be achieved by acquisition, joint ventures (of the type seen in the construction and modernization of breweries in China), and brand licensing and contract brewing. Brewing companies will become further polarized, into the ever bigger at one extreme and the very small at the other; those in the middle will find survival ever more challenging. More and more beer will be consumed at home, which is one of the justifications for increasing the shelf-life of the product: once a beer has been retailed, the Brewer has no further control over its handling. All the Brewer can hope to do is build robustness into the product.

"Robustness into the product": those are apt words with which to bring this journey to a conclusion. Brewers (and their colleagues, notably Maltsters and hop suppliers) have devoted themselves for many, many years to delivering to the public a wholesome and flavorsome product, robust and so very consistent, glass after glass.

Beer has a long and proud tradition. Thanks to more than a century of dedicated research, brewing has developed into a tightly controlled, efficient technological process, albeit one that is, unavoidably and fascinatingly, subject to the vagaries of its agricultural inputs.

Brewing is very much a science. Engage a brewer in conversation, though, and see the twinkle in his or her eye, and you will rapidly come to the conclusion that brewers love their brewing and their beer—just as any connoisseur loves his or her chosen art.

Appendix

Some Scientific Principles

I realize that not everybody reading this book will have received a scientific training—and some of those who did receive one may not have enjoyed it and, as a consequence, may have blotted it out of their memory banks. To help such people I offer here a simple crash course in chemistry, biology, and biochemistry, with just a little physics thrown in for good measure.

Elements and Compounds

All matter in this world, whether animal, vegetable, or mineral, consists of chemicals. One of the simplest of these—yet one of the most important—is water. Most of us know it as H_2O, which means that it is made up of two hydrogen atoms and one oxygen atom. An atom is the smallest unit of an *element,* and it is from the elements that all matter is composed. At last count there were over 100 elements. The simplest is hydrogen, which is given the symbol H. Other important ones include oxygen (O), nitrogen (N), sulfur (S), sodium (Na—after the Latin "natrium") and chlorine (Cl). Perhaps the key element in life is carbon (C). *Organic chemistry* is the chemistry of carbon *compounds.* The key components of living organisms are organic compounds, in that carbon is a key element in them.

A compound is a chemical entity, with its own individual properties, and consists of a collection of atoms of the same or different elements. The basic unit of a compound is a *molecule.* Water, H_2O, is a compound of hydrogen and oxygen. So, too, is hydrogen peroxide, H_2O_2. The latter molecule has just one extra oxygen atom, but this makes all the difference. Hydrogen peroxide is extremely reactive and finds uses as diverse as bleaching hair and sending rockets to the moon, not to mention stimulating barley to germinate. Water is, of course, a wonderful *solvent* (a solvent is something in which a *solute* can *dissolve:* for instance, if you add sugar to water, sugar is the solute and water the solvent). As we shall see, it is this ability to dissolve things that makes water so important to life—including the brewing of beer.

There are a great many *organic compounds*. Some are very simple—for example, natural gas consists of the simplest, *methane,* whose molecule consists of one carbon and four hydrogen atoms (CH_4). (Incidentally, carbon dioxide, CO_2, the compound that puts the fizz in beer, is *not* classified as an organic compound.) At the other extreme are very complicated molecules that consist of a great many carbon atoms, and other atoms, too. Here I will refer to those compounds that are relevant to living systems such as barley, hops, and yeast.

Carbohydrates

Starch is a carbohydrate; so too is sugar. In fact the term *sugar* refers to a wide range of related substances and not just *sucrose,* which is the granulated sugar that you stir into your coffee. The simplest sugar is *glucose,* which has the *formula* $C_6H_{12}O_6$. Like other sugars it is very sweet. Its formula is often written out as shown in figure A-1a, although sometimes it is represented as in figure A-1b.

This indicates that glucose (like other sugars) can exist in a *ring* form, the links (bar one oxygen atom) on the ring being carbon atoms, with the other atoms and groups of atoms protruding out. I show two ways of drawing glucose; in the second one, all but one of the carbon atoms have not been shown. This is standard practice when organic chemists draw formulae. You will find other examples in chapter 5, where the formulae of hop acids and cannabis resin are shown. Every time you see two lines join or a line end without another type of atom (e.g., H) signified, then there is a carbon atom at that point.)

Sugars such as glucose are able to join together to make bigger molecules. They do this by splitting out a molecule of water between them. If two glucoses join together, they make *maltose* (see fig. A-1).

Now if water is added to maltose, then the *reverse* reaction can occur, and it will be split into two glucose molecules. When water is used to break up a molecule in this way it is called *hydrolysis*. Usually this reaction doesn't happen spontaneously: for instance, if you dissolve maltose in water, very little of it is hydrolyzed to glucose. Maltose needs help to be broken down, and this help comes in the form of *enzymes,* which I will come to shortly.

Maltose can pick up another glucose, and the resultant sugar is malto*tri*ose (*tri* indicating that this molecule contains three glucoses). Add a fourth glucose, and you have maltotetraose, and so on. Each of these molecules, with one, two, three, four, and so on, glucose units has different chemical properties. For example, they are progressively less sweet.

Molecules containing relatively short chains of glucose units are known as *dextrins*. Sometimes they are called *oligomers,* and the basic building block, glucose, is called a *monomer* ("mono" means "alone"). When there are lots and lots of building blocks, in this case glucose linked together, we have a *polymer.* In the case of polymerized glucose, the best known molecule is *starch,* which is the major food reserve in the barley grain. Polymers of sugars are called *polysaccharides;* the building blocks (in this case glucose) are called *monosaccharides;* dextrins are *oligosaccharides*.

A molecule such as glucose can join together in different ways. If the links between the glucoses are in a certain configuration in three-dimensional space (the so-called α-conformation), then the resultant polymer is α-glucan, or starch. If, how-

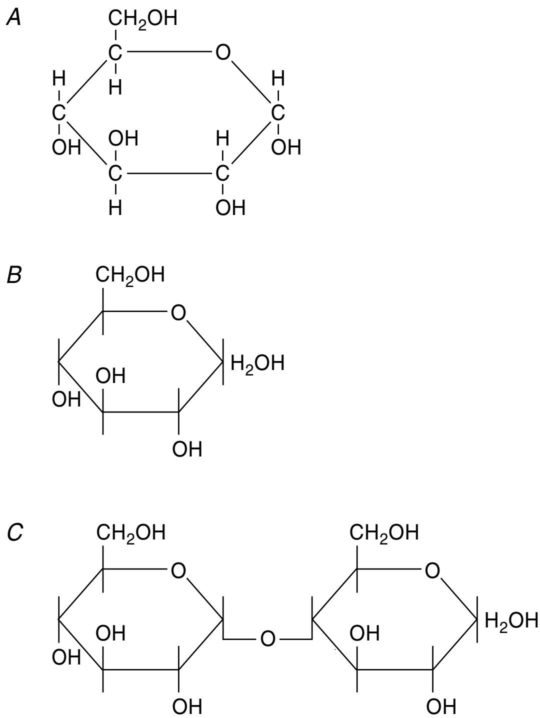


Figure A1 *Structures of sugars: (A) Glucose; (B) Glucose—short hand; (C) Maltose.*

ever, the links have a β-conformation, then the resultant polymer is a β-glucan, which has a totally different set of properties from starch. The latter is the main component of the barley cell wall, for instance, whereas starch is the food reserve packed within those cell walls.

Proteins

A different type of polymer found in living systems is *protein*. Here the monomer is not sugar but rather *amino acids*. These are simple molecules that, unlike sugars, contain nitrogen atoms. There are 20 or so different amino acids, each of which has different properties. Just like sugars, they can link together, by splitting out water, to form long chains. Again, as for polysaccharides, the reverse process can take place, and addition of water to a polymer of amino acids leads to hydrolysis to individual amino acids (provided the proper enzyme is present—see hereafter).

When a few (say 2–10, although the exact definition is somewhat arbitrary) amino acids are linked together, the molecule formed is called a *peptide*. A molecule containing, say, 10–100 amino acid monomers is called a *polypeptide*. Bigger molecules are called *proteins*.

Because there are different amino acids, they can be linked together in many different sequences, and thus there is tremendous diversity among proteins in their structure and properties. Egg white is composed of protein; so are the nails on your fingers and the silk in your tie or your dress. They are all very different.

The proteins in nails or silk are *structural* proteins. Another very important class of proteins is the *enzymes*. These are found throughout biological systems and are *catalysts*. A catalyst is a compound that speeds up or enables a chemical reaction to take place. For example, I mentioned earlier that if two glucoses link together they form maltose. This joining-together doesn't happen spontaneously, it has to be catalyzed. There is an enzyme that does that job. There is also a different enzyme that enables the reverse reaction, that is, the breakdown of maltose into glucose by the addition of water. Because it catalyses a hydrolysis, it is called a *hydrolase*. Wherever you see the suffix *-ase,* it refers to an enzyme. Synthases catalyze synthetic reactions, such as the coupling of two molecules together. Decarboxylases split carbon dioxide out of molecules. Oxidases add oxygen to molecules, whereas dehydrogenases take hydrogen out of molecules. There are many different enzymes, each of which has its *specific* job to do.

For the most part an organism will only produce an enzyme when it needs it to do a job of work. Take barley, for instance. When it is ready to germinate, it needs to break down the food reserves in its starchy endosperm. First of all it needs to break down the cell walls that are the wrapping in the endosperm, so it needs first to make the enzymes that do this job. Key among these enzymes are the β-glucanases, so these are the first enzymes to be produced by the protein-synthesizing machinery in the aleurone tissue, which responds to a specific hormone trigger from the embryo (see chapter 4). (*Hormones* are molecules, usually small ones, that signal that a specific change needs to take place in a living system. They don't make that change themselves.)

Once the walls are gone, then the barley needs the *proteinases* to break down the proteins, exposing the starch, which, in turn, is hydrolyzed by the *amylases*. (As shown in chapter 4, the key components of starch are amylose and amylopectin, hence the name of the enzymes that degrade them.)

β-Glucanases, proteinases, and amylases are different enzymes. They each have their own job to do. By ensuring such specificity in enzymes, living organisms can maintain control over their *metabolism* (an organism's metabolism is the sum total of all the reactions involved in its life cycle).

To act, enzymes need to get close to the molecules that they act on (the *substrates*). The reaction will generally only occur when there is water present within which the enzyme and substrate can move around. This is the reason why water must be introduced into barley before its metabolism can swing into action, but then driven off from malt in kilning when the Maltster wishes to stop the modification process. It's also why you must add water to milled malt to get the starch hydrolysis reactions going.

All chemical reactions take place more rapidly at higher temperatures, the rule of thumb being that the reaction rate doubles for each 10°C rise in temperature. This applies to enzyme reactions, too, but there is a complication. Enzymes are, to a greater or lesser extent, inactivated by heat. Some are very sensitive and are rapidly killed at relatively low temperatures, such as 50°C. The β-glucanases are an example of this high *lability*. Other enzymes are more robust; for example, some of the peroxidases (enzymes that use hydrogen peroxide as a substrate) in barley happily survive 70°C. These varying sensitivities to heat have major implications for the malting and brewing processes, as shown, for example, in chapters 4 and 6.

Other Complex Materials in Living Systems

There are two other key classes of complex molecules found in all living systems, including barley, hops, and yeast: the nucleic acids and the lipids. It is not necessary to go into any great detail here, but suffice to say that the *nucleic acids* are the molecules that are involved in synthesizing the proteins of an organism. They contain the genetic code that determines the nature of an organism: whether it is a man or an amoeba, a barley or a hop, a yeast or an organism intent on spoiling beer. There are two types of nucleic acid: deoxyribonucleic acid (DNA) and ribonucleic acid (RNA). The former is the genetic code, or blueprint; the latter provides the protein-synthesizing machinery.

There are many types of *lipids* in cells. Most of them contain very long chains of carbon atoms linked to hydrogen, so-called fatty acids. Their only property that I want to mention here is that, by definition, they are not soluble in water but rather in other types of solvent. There is a saying in chemistry that *like dissolves like.* Lipids dissolve in *organic solvents.* This is essentially the definition of a lipid. I refer you to the home for the simplest explanation. Think of a sugar such as glucose; you will see from its formula (see earlier) that it has lots of -OH groups on it, rather like water: H_2O or, if you like, H-O-H. Glucose readily dissolves in water. Now think of a greasy spot on your clothes caused by butter. Butter is composed of lipid, and you won't get rid of that stain by washing with water. You will need a solvent that also has a long carbon chain, something like petroleum. Because of this insolubility, lipids tend to be associated with structural elements in a living organism, and in a process such as brewing, they tend to associate with particles, such as the spent grains. Cooking fats, lipstick, and glass-washing detergents are all lipids, because of their water-insolubility, and if they get into beer they will tend to go into the foam rather than the liquid beer. Once in the foam, they disrupt it—and kill it (see chapter 3). My wife can pretty much deliver the funny lines from my classes, especially this one: if you're dripping fat off your moustache, you will have a lousy foam on your beer; if you are wearing lipstick, then you will have just as big a nightmare; if you have a moustache *and* lipstick then you have real problems.

Cells

The fundamental unit of all living organisms is the cell. Some organisms, such as brewing yeast, are *unicellular,* in that they consist of just one cell. Organisms such as barley and hops are *multicellular,* with many different types of cells. Thus, in barley, there are embryo cells, aleurone cells, starchy endosperm cells, and so on. Collections of similar cells (for example, the aleurone) are called *tissues.*

The bacteria that can contaminate wort and beer are also unicellular, but they are even simpler than yeast. In a bacterium there is no division of the contents of the cell into compartments: all of the nucleic acids, carbohydrates, proteins, and other simpler molecules that are involved in the metabolism of the bacterium are in a watery soup called the *cytoplasm.* Such simple organisms are called *prokaryotic.*

The cells of yeast and other *higher* organisms (such as barley and hops) are *eukaryotic:* the cytoplasm is divided into distinct regions, called *organelles.* Just as the organs of the human body have their own roles, so too do the organelles within a cell have their own functions. These are referred to in the context of yeast in chapter 7.

Living cells need a source of energy that when released, they use to survive, to grow, to divide, or to do the job "allocated" to them. A cell in the embryo of barley will consume energy in making the hormones that it will send out to the aleurone cells, which in turn consume energy in producing the hydrolytic enzymes that will degrade the starchy endosperm. In organisms such as yeast and the barley grain, the energy is obtained by "burning" sugars: in a series of enzyme-catalyzed reactions, the sugar is degraded, and energy is progressively released. The standard equation for *respiration* is given in chapter 7, as well as the equation for when the process is carried out in the absence of oxygen (*fermentation*). In both instances the energy is collected in the form of a chemical carrier called ATP, which is found in all living cells and is often called the "universal energy currency"; ATP is then used by the energy-consuming reactions, such as movement of cells, synthesis of new proteins and membranes, and so on.

Food Reserves Are Polymers—Why?

Wouldn't it be easier if the cells of the starchy endosperm of barley were packed full of glucose and amino acids rather than starch and protein, so that all the embryo had to achieve was to open up of the wrapping cell wall and then bathe in the flood of goodies that would surge out? Yes, it would, but it isn't possible; in the same way, yeast must keep its food reserve, glycogen, in a polymeric form.

We have to understand the phenomenon of *osmosis* to appreciate the reason for this polymeric storage. If you have two liquids, one a concentrated solution of glucose and the other a dilute solution of glucose, and you separate them by a membrane, then water will progressively pass from the dilute solution to the more concentrated one, until the strength of the solutions is identical on either side of the membrane. This is osmosis. The numbers of glucose molecules on either side of the membrane are critical in this experiment. Now, if those glucoses were all linked together as starch (see earlier) then, instead of having many molecules of sugar in the concentrated solution, we would just have a single molecule. There is the same amount of sugar, but far less *osmotic pressure*. Herein we find the reason for the polymeric form of food reserves: if all the glucose and amino acids in the starch and protein food reserves of barley were monomeric, they would exert an enormous osmotic pressure in the cells, and water would flood into them and burst them.

pH

pH is a measure of the relative acidity or alkalinity of a solution. Although there are several definitions of an acid, here it's sufficient to say that it is a chemical substance that releases *hydrogen ions*. pH is a measure of the concentration of hydrogen ions: it might seem backward, but the lower the pH number, the more hydrogen ions are present and the more acid the solution. The symbol for the hydrogen ion is H^+. It has one positive "charge." Ions are basically chemicals that have charges. They attract or repel other ions: one positive ion will repel another positive ion, but it will attract a negative ion. The saying goes: "Like charges repel, opposite charges attract."

One negatively charged ion is the hydroxide ion, OH^-. If a hydrogen ion and a hydroxide ion get together by attraction, they can go as far as to react with one another and make . . . yes, water!

$$H^+ + OH^- \rightarrow H_2O$$

Clearly, if all of the hydrogen ions in a solution are mopped up by hydroxide ions, then the solution is neutral and not acidic. Its pH is 7.0. If there are more hydrogen ions than hydroxides, then the pH is below 7 and is acidic. The lower the pH, the more acid the solution. If there are more hydroxide ions than hydrogen ions, the solution is alkaline (caustic) and has a pH above 7.0.

Beer is acidic, with a pH usually between 3.8 and 4.6.

Hydroxide isn't the only negatively charged species that the hydrogen ion can react with. Others include the bitter substances, the iso-α-acids; they can exist in a charged, negative state at higher pHs, but when the pH is low (H^+ is high) they "pick up" this ion, and the charges cancel out, that is, they become uncharged. This type of interaction is tremendously important. In the case of these hop compounds, it influences their bitterness and foaming properties. The uncharged forms are much bitterer, more foaming, and better able to kill microorganisms than the charged forms. For this reason, too, enzymes are more or less active at different pHs, because they too can have different structures, depending on the extent to which their negative groups interact with the hydrogen ion.

Buffers are materials that can chemically "soak up" hydrogen ions and therefore stop a pH changing. They are very important in living cells, because the pH needs to be kept fairly constant as the cell's machinery is designed to operate to best effect at that pH.

The starchy endosperm cells in barley and malt, therefore, have their preferred internal pH. A mash of malt will have a pH of around 5.5, due to an "internal" buffering system (including some of the soluble proteins, polypeptides, and peptides) that holds the pH at that value. Quite a lot of acid needs to be added to drop the pH from that value. The pH falls during mashing because the yeast uses up the buffering system (peptides) and because the yeast releases acid.

One factor involved in lowering the pH in a mash is the level of calcium in the water (liquor). Calcium reacts with phosphate from the malt, releasing hydrogen ions, as follows.

$$3Ca^{2+} + 2HPO_4^{2-} \rightarrow Ca_3(PO_4)_2 + 2H^+$$

Color

The color of a liquid such as beer, or one's clothes, or the cover of this book—of all things—is due to the extent to which the eyes detect different types of light.

Light can be thought of as a vast collection of different waves, each of which has a different size (wavelength), measured in nanometers (nm; 1 nm is one thousand-millionth of a meter). Visible light is a collection of light waves of anything between 400 nm and 800 nm. Blue light is at the shorter wavelength end, red light at the longer wavelength end.

If you have a light source equally strong at all of these wavelengths, then the light you see is vivid white. Conversely, if there were no light whatsoever, you would see black. You would also see black if somebody put a filter between your eyes and a light source, a filter that screened out light at all the wavelengths. If, however, that filter sifted out only the longer wavelength light, then you would detect the light as being blue, because it is the shorter wavelengths that are reaching the eye. If the filter trapped the shorter wavelengths, then you would see red light emerging.

This is the basis of seeing different colors. Paints and pigments are the color they are because they absorb a series of wavelengths of sunlight *other* than those that are associated with the color that they reveal to you. A green paint has the shade it has due to a selection of wavelengths of light that it doesn't filter out and that therefore enter your eye.

Many individual chemical compounds absorb light of specific wavelengths, and this is the basis for measuring them. Take our friends the iso-α-acids again: they absorb what is known as ultraviolet light, which is very short wavelength light—beyond the blue light at the lower wavelength end of the spectrum, light that cannot be detected by the human eye. By measuring the amount of such light that is absorbed by a solution of the iso-α-acids, one can deduce how much of these materials are present, because the more of a chemical compound is present in a solution, the more light it will absorb. To measure these bitter compounds, then, they are extracted into a solvent, and light with a wavelength of 275 nm is shone through the solvent. This is done in a spectrophotometer, which is a device that can split up light into individual wavelengths and measure how much of each wavelength is "taken out" by a solution. Spectrophotometry, using a wide range of wavelengths appropriate to the chemical to be measured, is extensively used in industry, including the brewing industry. At the longer wavelengths (beyond the red end of the spectrum) we come across the near infrared (NIR) region. A number of chemical species absorb radiation in this part of the spectrum, including water and protein. This is taken advantage of in NIR spectroscopy to measure materials very rapidly, notably in the screening of barley entering into a maltings after harvest; NIR can also be used for in-line measurement of alcohol in the brewery.

Chromatography

Another analytical technique of enormous value in the brewery is chromatography. Basically this involves the separation of mixtures by passing a mobile phase past a stationary phase. Substances differ in their preference for the two phases and are either held on the stationary phase or tend to move along with the mobile phase. When the chromatography is complete, the individual substances are detected in some way, perhaps by measuring their absorption of specific wavelengths of light (see earlier), staining them with a dye, and so on. There are various types of chromatography: in gas chromatography the mobile phase is a gas mixture and the stationary phase some type of solid in a column. High-performance liquid chromatography differs in that the mobile phase is a liquid at very high pressures.

Glossary

Abrasion Damaging the part of the barley corn farthest from the embryo in order to stimulate activity of the aleurone and "2-way" modification.

Abscisic acid A plant hormone that counters the action of gibberellic acid.

Accelerated fermentation Fermentations carried out under conditions where they proceed more rapidly, e.g., by operating at a higher temperature.

Acid washing Treating yeast with acid in order to kill contaminating organisms without destroying the yeast itself.

Acrospire The developing shoot in germinating barley.

Adjunct A source of fermentable extract other than malt for use in brewing.

Aerobic In the presence of oxygen.

Aging The holding of beer in order for it to be converted to the desired state for retail to the consumer.

Agitator A device for mixing the contents of a vessel, e.g., a mash mixer.

Air rest Period employed during the steeping of barley in which water is drained from the grain bed to allow the access of oxygen to the embryo.

Albumin Soluble protein class in barley.

Alcohol Alcohols are a class of organic compounds containing the hydroxyl (-OH) group. The principle product of fermentation by yeast is ethyl alcohol (ethanol). Other, "higher" alcohols are also produced in much lower quantities by yeast, and they are implicated in the flavor of beer.

Alcoholic strength (ABV) The amount of alcohol in a beverage, frequently referred to as ABV (alcohol by volume), in which the ethanol content is quantified in terms of volume of ethanol per volume of beverage.

Ale A type of beer generally characterized by an amber color and traditionally produced using a top-fermenting yeast. (In medieval England, *ale* meant unhopped beer, but this no longer applies.)

Aleurone Tissue two to three cells deep that surrounds the starchy endosperm of the barley corn and is responsible for making the hydrolytic enzymes (hydrolases) that degrade the barley food reserves.

Alpha acids Resins from the hop that are the precursors of the bitter compounds in beer.

Amino acids Small molecules (there are around 20 different ones) containing nitrogen, which are the building blocks of proteins.

Amylases Starch-degrading enzymes.

Amylose A linear polymer of glucose that is a key component of starch.

Amylopectin The second key component of starch, differing from amylose in that it has branches.

Anaerobic In the absence of oxygen.

Aneuploid Indicates that an organism contains more than two copies of its genetic blueprint. (Haploid organisms contain one copy; diploid organisms contain two copies; polyploid organisms contain many. There is no agreed-on point at which aneuploidy becomes polyploidy.)

Antifoam A material added to fermentations to suppress excessive production of foam.

Antioxidant A material (either native to a raw material or added) that serves to protect against the damaging influence of oxygen.

Aroma hops Hop varieties said to give particularly prized aroma characteristics to a beer.

Astringency A drying of the palate.

ATP bioluminescence A technique for detecting microorganisms and soil by measuring the amount of light produced by the action of the enzyme luciferase acting on ATP present in the sample.

Autolysis The breakdown of a cell by its own enzymes.

Auxillary finings Agents used alongside isinglass to facilitate the settling of insoluble materials from green beer.

Awn The beardlike projection on a barley corn.

Barley *Hordeum vulgare;* a member of the grass family and the principle raw material for malting and brewing worldwide.

Barley wine A very strong type of ale of long standing in England.

Barrel A volume measure of beer (in the United States, 31 U.S. gallons or 1.1734 hectoliters; in the United Kingdom, 36 UK gallons or 1.6365 hectoliters).

Beading The formation of bubbles of carbon dioxide in a glass of beer and their rise to the top of the drink.

Beer stone A precipitation of calcium oxalate in beer dispense pipes.

Beta-glucan (β-glucan) A polymer of glucose that forms the bulk of the cell walls in the starchy endosperm of barley; causes several serious problems to the brewer if not properly broken down in malting and mashing.

Beta-glucanase (β-glucanase) The type of enzyme that hydrolyses β-glucan.

Biological acidification A practice, common in Germany, in which microorganisms (lactic acid bacteria) are encouraged to grow in the mash in order to increase the acidity (lower pH).

Biological stability The extent to which a beer is able to resist infection.

Bitter A type of draft ale that is not excessively colored.

Bitterness A flavor characteristic customarily associated with beer; also the term used to quantify the content of bitter compounds (iso-α-acids) in beer.

Bock A type of lager-style beer.

Boiling The process of vigorously heating sweet wort at boiling temperatures.

Bottom fermentation Traditional fermentation mode for lagers; yeast collects at base of fermenter.

Bracteoles The leafy parts of a hop cone.

Breakdown Deterioration of a beer.

Break point The stage during kilning of malt when the temperature of the air leaving the malt starts to increase, because all of the free water that is not inside the malt has been driven off. Whenever there is unbound water present, it will consume energy (latent heat) in order to escape, essentially as steam. If this free water is taking up the heat, then the air coming off the kiln remains relatively cool.

Brewhouse The part of the brewery where grist materials are converted into wort.

Brewster A female brewer.

Bright beer Beer postfiltration.

Bright beer tank The vessel to which a beer is run after filtration and before packaging; sometimes called a fine ale tank.

Bromate A salt; has been employed (as potassium bromate) in order to suppress rootlet development during germination of barley.

Burtonization Adjustment of the salt content of brewing liquor to render it similar to that of the water at Burton-on-Trent in England.

Calandria A device either internally or externally linked to a kettle and used for heating wort.

Calcofluor A substance that binds specifically to β-glucans and reveals them via fluorescence.

Carbonation The amount of carbon dioxide in a beer and also the act of increasing the level of carbon dioxide.

Carboxypeptidase An enzyme in barley that hydrolyses proteins by chopping off one amino acid at a time from one end.

Cardboard An undesirable flavor note that develops in packaged beer in storage.

Carrageenan An extract of seaweed used to aid solids removal in the wort-boiling stage.

Cask The traditional vessel for holding unpasteurized English ale.

Cell The basic unit of any living organism.

Cellar The part of a brewery containing the fermenters and the conditioning vessels. Also the part of a retail outlet (e.g., bar) in which the beer containers are stored.

Cell wall The outside of a cell, whose role is to maintain the shape of that cell.

Charcoal A material capable of adsorbing flavors and colors from liquids it contacts; used, for example, to treat liquor coming into a brewery.

Chilling The cooling of liquid streams in a brewery, e.g., hot wort going to the fermenter, or green beer passing to conditioning and filtration.

Chromosome The forms in which the genetic material of a cell (DNA) is held in eukaryotic cells.

CIP (cleaning-in-place) An integrated and automated system of cleaning with caustic and/or acid installed in modern breweries.

Cling The adhesion of foam to the walls of a beer glass (also known as lacing).

Coalescence The tendency of bubbles in beer foam to merge together and form bigger bubbles.

Cold break Insoluble material that drops out of wort on chilling.

Cold water extract A measure of modification of malt based on the small scale extraction of milled malt in dilute ammonia.

Colloidal stability The tendency of a beer to throw a haze on storage.

Color The shade and hue of a beer.

Conditioning The maturation of beer in respect of its flavor and clarity.

Continuous fermentation A process in which wort is converted to green beer in a few hours by passage through a vessel holding yeast.

Conversion The stage in mashing when the temperature is raised to enable gelatinization of starch and subsequent breakdown of the starch by amylases.

Cooker A vessel in the brewhouse in which adjuncts with very high gelatinization temperatures are cooked.

Cooler A device (often called a paraflow) in which hot wort flows contra to a cooling liquid in order to bring it down to the temperature at which fermentation will be carried out.

Copper The vessel (often called the kettle) in which wort is boiled with hops.

Corn Maize. The word is also used to describe individual grains of barley.

Crabtree effect The control mechanism that dictates that yeast ferments sugar rather than metabolizing it via respiration if the sugar concentration presented to the yeast is high.

Cropping The collection of the yeast that proliferates during fermentation.

Crown cork The crimped tops used on beer bottles.

Culms The rootlets of germinated barley that are collected after kilning and sold as animal feed.

Curing The higher temperature phases of kilning when flavor and color are introduced into malt.

Cylindroconical vessels (CCVs) Tall fermentation vessels with a mostly cylindrical body but a conelike base in which the yeast collects after fermentation.

Darcy's law Equation that explains the rate at which liquid flows, e.g., in a lauter tun or a beer filter.

Decoction mashing Practice, originating in mainland Europe, in which a mash is progressively increased in temperature by taking a proportion of it out of the mix and boiling it prior to adding it back into the whole.

Descriptive tests Beer-tasting protocols in which trained tasters describe the taste and aroma of beer according to a series of defined terms.

Dextrins Partial breakdown products of starch that consist of several glucose units and are not fermentable by yeast.

Diacetyl A substance with an intense aroma of butterscotch that is produced by yeast during fermentation but is subsequently mopped up again by the yeast.

Diatomaceous earth The skeletal remains of microscopic organisms used in powder filtration of beer (also known as kieselguhr).

Difference tests "Blind" tasting procedures in which tasters (including the untrained) are asked to differentiate samples of beer.

Dimethyl sulfide (DMS) Compound that imparts a significant flavor to many lager-style beers.

Dirty wort Wort that contains a high level of trub solids and is therefore turbid.

Disproportionation The passage of gas in beer foam from small bubbles to larger bubbles, leading to a disappearance of the former and increase in size of the latter.

Dissolved oxygen The amount of oxygen dissolved in a wort prior to fermentation or, more commonly, the amount dissolved (and undesired) in beer.

Dormancy The control mechanism in barley that prevents the grain from germinating prematurely.

Downy mildew A disease of hops.

Draft beer Beer in cask or keg; sometimes unpasteurized beer in small pack.

Drinkability The property of beer that determines whether or not a customer judges it worthy of repurchase.

Dry beer Beer genre in which beverage contains relatively low residual sugar.

Dry hopping Traditional procedure in the production of English cask ales in which a handful of hop cones are added to the cask prior to shipment from the brewery.

Duty Excise tax on beer.

Dwarf hops Hops that grow to a lower height than traditional varieties.

Ear The head of a barley plant that holds the grain.

Embryo The baby plant in the grain.

Endo enzymes Hydrolytic enzymes that chop bonds in the inside of a polymeric substrate (examples are α-amylase and β-glucanase).

Endogenous enzymes Enzymes in the malting and brewing process that are contributed by the raw materials (malt and yeast).

Endosperm The food reserve of the barley plant.

Enzyme A biological catalyst consisting of protein.

Essential oils The aromatic component of hops.

Ester A class of substances produced by yeast; affords distinctive, sweet aromas to beer.

Ethanol The principal alcohol in beer; it is the major fermentation product of brewing yeast and affords the intoxicating property to the beverage. Originally called ethyl alcohol.

Evaporation A measure of the water loss during wort boiling.

Excise Tax on alcoholic beverages levied by government agencies.

Exo enzymes Hydrolytic enzymes that chop bonds at the ends of substrate molecules, thereby yielding small products generally assimilable by organisms (examples are β-amylase and carboxypeptidase).

Exogenous enzymes Enzymes added to the brewing process from outside sources (i.e., not from malt or yeast).

Feed grade barley Barley that yields a relatively low level of extractable material after conventional malting and mashing.

Fermentability The extent to which a wort can be used successfully by yeast to produce ethanol.

Fermentation The process by which sugars are converted into ethanol by yeast.

Filtration The clarification of beer (sometimes people refer to the recovery of wort from spent grains as "filtration," but strictly speaking, this is "wort separation").

Fingerprinting The differentiation of yeasts (or barleys) by analyzing the pattern of DNA fragments produced from them.

Finings Materials used to clarify wort, and especially beer; they interact with solid materials and cause them to sediment.

Flash pasteurization Heating of flowing beer to a high temperature (e.g., 78°C) for less than a minute in order to inactivate microorganisms.

Flavor profile An expert semiquantitative evaluation of beer flavor made by trained tasters using defined taste and aroma descriptive terms.

Flavor stability The extent to which a beer is able to resist flavor changes (usually undesirable) within it.

Flocculation The tendency of yeast cells to associate.

Foam The head (froth) on beer.

Foam stabilizer Either endogenous materials (e.g., proteins from malt) that stabilize foam or materials added to beer to protect foam (e.g., propylene glycol alginate).

Font The unit on the bar that labels the draft beer being served from that tap.

Franchise brewing The brewing of one company's beer under license by another company.

Free amino nitrogen (FAN) A measure of the level of amino acids in wort or beer.

Fungicide An agent sprayed onto crops such as barley and hops to prevent the growth of fungi thereon and therefore ensure that those crops are healthy and high yielding and don't introduce any harmful materials into the brewing process.

Fusarium An infection of barley that can cause a beer made from that barley to gush.

Gallon A standard unit of beer volume.

Gelatinization A disorganization and loosening of the internal structure of starch granules by heating, rendering the starch more amenable to enzymic hydrolysis.

Genetic modification A process of modifying the genome of an organism by introducing specific pieces of DNA from an exogenous source.

Genome The information code of a cell, held within DNA, which determines the nature and behavior of that cell.

Germination The process by which steeped barley is allowed to partially digest its endosperm and the embryonic tissues to partially grow.

Gibberellins Plant hormones, produced within the embryo of barley, that migrate to the aleurone and trigger enzyme synthesis.

Gravity The strength of wort in terms of concentration of dissolved substances, as measured traditionally, using a hydrometer.

Green beer Freshly fermented beer prior to conditioning.

Green malt Freshly germinated malt prior to kilning.

Grist The raw materials (malt and other cereals) that are milled in the brewhouse. More loosely applied also to those adjunct materials that don't require milling (e.g., syrups to be added to the kettle).

Gushing The uncontrolled surge of the contents of a beer from the package after opening.

Hammer mill A mill that grinds malted barley down to extremely fine particles that are suited to a mash filter for subsequent wort separation, but not a lauter tun.

Haze Turbidity.

Hazemeter An instrument for measuring the clarity of beer: operates on the principle that particles scatter light. The more light scattered, the more particles are present. Some hazemeters measure the amount of light scattered at right angles (90°) to the light beam shone at the particles. Other meters ("forward scatter" meters) measure the light deflected at 13°. The former type is sensitive to extremely small particles, the latter to big particles.

Heat exchanger Device for rapidly cooling down liquid streams, e.g., boiled wort. The hot liquid flows countercurrent to a cold liquid on either side of thin walls. Heat passes from the hot to the cold liquid.

Hectoliter 100 liters.

Hemocytometer Microscope-based chamber for counting yeast cells.

High-gravity brewing Technique for maximizing vessel utilization whereby the wort being fermented is more concentrated than necessary to make the desired strength of beer. After fermentation, the beer is diluted to the required alcohol content.

High-performance liquid chromatography (HPLC) Analysis technique involving separation and measurement of components of a mixture on the basis of their relative affinity for a high-pressure liquid stream or a solid support. In gas chromatography (Gc) the liquid is replaced by gas.

High-temperature mashing Mashing performed at higher than normal temperatures in order to rapidly eliminate one of the starch-degrading enzymes (β-amylase) and produce a wort that contains fewer sugars that are fermentable by yeast and hence a lower-alcohol beer.

Higher alcohols Compounds that are similar to ethanol but contain more carbon atoms. They may contribute to the aroma of beer (and certainly do after conversion into their equivalent esters), and it has been suggested that they may be responsible for hangovers, although there is very little evidence for this.

Hop Plant that provides bitterness and aroma to beer.

Hop back Vessel, rarely found these days, that was used to separate boiled wort from residual solids by passage through a bed of waste hops.

Hop cone The flower of the female hop plant, which is the part of the plant used in the brewing process.

Hop garden Where hops are grown. Also known as hop yard.

Hop oil The component of hops providing aroma (essential oils).

Hop pocket A large sack packed with hops.

Hop preparations Extracts of hops, usually made with liquid carbon dioxide; can be used at various stages in the brewing process to introduce bitterness or aroma to wort or beer more efficiently.

Hop resin The precursors of bitterness in beer (α-acids).

Hopped wort Wort after the boiling stage.

Hordein Insoluble storage protein in barley that is broken down during malting and mashing.

Hormone Small molecule that switches on or off events in a living organism; e.g., gibberellins are hormones that switch on enzyme synthesis in barley.

Hot break Insoluble material that drops out of wort on boiling.

Hot water extract A measure of how much material can be solubilized from malt or an adjunct, obtained by carrying out a small-scale mash of the material and measuring the specific gravity of the resultant wort.

Husk The protective layer around the barley corn. Also known as hull.

Hydrogel Material derived from acid treatment of silica that is used for the removal of potential haze-forming materials from beer ("chillproofing").

Hydrolyzed corn syrup Material produced by the acid or enzymic hydrolysis of corn starch; can have different degrees of fermentability. It is added to the wort kettle, thereby providing an opportunity to extend brewhouse capacity by avoiding the need for mash extraction and separation stages.

Hydrometer Device operating on a principle of buoyancy for measuring the specific gravity of a solution: the higher it floats, the more material is dissolved in the solution.

Hydrophobicity A measure of the extent to which a molecule moves away from water; such molecules are hydrophobic. Grease and fats are hydrophobic, whereas salt is hydrophilic ("water-loving").

Ice beer Beer produced with a process that includes ice generation.

Immobilized yeast Yeast attached to an insoluble support (e.g., glass beads) that can be used in continuous processing whereby wort or beer is flowed past it.

Indirect heating Heating of a material without direct application of heat, but rather via a heat exchanger.

Infestation Condition whereby a raw material in the maltings or brewery has animal life within it, e.g., insects in badly stored barley.

Inorganic Any chemical species other than those containing carbon. (Note: carbon dioxide, despite containing carbon, is regarded as inorganic.)

Insecticide Material sprayed onto crops either during growth or storage to eliminate insect infestation.

Invisible haze Haze that registers on a hazemeter but is not perceptible to the eye; sometimes called pseudohaze.

Iron Inorganic element that can enter into beer from some raw materials (e.g., filter aids) and potentiate oxidative damage.

Isinglass Preparation of solubilized collagen from the swim bladders of certain fish, used for clarifying beer; normally referred to as "finings."

Iso-α-acid Bitter component of beer derived from hops.

Isomerization The conversion of hop α-acids into iso-α-acids, achieved during wort boiling.

Keg Large container for holding beer, for subsequent draft dispense by pump.

Kettle Brewhouse vessel in which wort is boiled; also known as "copper."

Kieselguhr Mined powder, derived from skeletons of microscopic animals, used to aid the filtering of beer.

Kilning Heating of germinated barley to drive off moisture and introduce desired color and flavor.

Krausening Traditional German fermentation practice in which fresh fermenting wort is introduced late during warm conditioning to stimulate the maturation of the beer.

Lacing Tendency of beer foam to stick to the side of the glass (also known as cling).

Lager A type of beer, traditionally pale, produced by bottom-fermenting yeast and produced in a relatively slow process, which includes lengthy cold storage ("lagering"). The word "lager" is derived from the German "to store."

Large pack Kegs or casks.

Late hopping Practice of adding a proportion of the hops very late in the wort-boiling phase in order to retain certain hop aromas in the beer.

Late hop essences Extracts that can be added to beer to introduce a late hop character.

Lauter The act of separating sweet wort from spent grains; the vessel used to perform this duty.

Lead conductance value A method for assessing how much bitterness precursor is present in hops.

Light (lite) beer Beers in which a greater proportion of the sugar has been converted into alcohol.

Lightstruck Refers to a skunky flavor that develops in beer exposed to light.

Limit dextrinase Enzyme in malt that breaks the branchpoints in the amylopectin component of starch.

Lipid A material that does not dissolve in water but does dissolve in organic solvents.

Liquid carbon dioxide Solvent produced by liquefying carbon dioxide gas at low temperatures and high pressures; used for extracting materials from hops.

Liquor Water.

Low-alcohol beers Beers containing a low level of alcohol (e.g., less than 2% ABV, although the definition differs among countries).

Lupulin The glands in hop cones that contain the resins.

Malt Dried germinated barley.

Malting The controlled germination of barley involving steeping, germination, and kilning so as to soften the grain for milling, to develop enzymes for breaking down starch in mashing, and to introduce color and desirable flavors.

Malting grade Score allocated to a barley variety that indicates whether it will give a high hot water extract after conventional malting and mashing.

Masher Device positioned before the mash mixer that facilitates intimate mixing of milled malt and hot liquor. Sometimes called "pre-masher."

Mashing Process of contacting milled grist and hot water to effect the breakdown of starch (and other materials from the grist).

Mash filter Device incorporating membranes for separating wort from spent grains.

Mash tun Vessel for holding a "porridge" of milled grist and hot water to achieve conversion of starch into fermentable sugars.

Mashing off Conclusion of mashing, when the temperature is raised prior to the wort separation stage.

Maturation The postfermentation stages in brewing when beer is prepared ready for filtration.

Mealy Favorable texture of the starchy endosperm of barley that makes it easy to modify.

Melanoidins Color contributors in beer produced by the reaction of sugars with amino acids during heating stages in malting and brewing.

Membrane A sheet, either one found in a living system (e.g., the plasma membrane that surrounds a yeast cell) or one that has a specific job to do in a brewery (e.g., in a mash filter or a beer filter).

Metabolism The sum of the many chemical reactions that are involved in the life of a living organism such as barley or yeast.

Micropyle The area at the embryo end of a barley corn through which water can gain access.

Milling The grinding of malt and solid adjuncts to generate particles that can be readily broken down during mashing.

Mitochondrion The organelle in a eukaryotic cell responsible for generating energy in respiration.

Modification The progressive degradation of the cell structure in the starchy endosperm of barley.

Moisture content The amount of water associated with a materials such as barley, malt, hops, or yeast.

Mold Infection of barley or hops.

Mouthfeel The "tactile" sensation a beer creates in the mouth (also referred as texture).

Near infrared (NIR) A region of the light spectrum where wavelengths are longer than those in the visible red region but shorter than those in the infrared region; NIR spectrometers are increasingly widely used for making various rapid measurements in the maltings and brewery.

Nitrogen There are two completely separate meanings for nitrogen in malting and brewing: (1) the nitrogen atom (N) as it is found in proteins; therefore, its level in barley, malt, or wort is a measure of how much protein they contain; (2) gaseous nitrogen (N_2), which is sometimes introduced into beer to enhance foam. This process of introduction is called nitrogenation.

Nonalcoholic beers Beers containing very low levels of alcohol, e.g., less than 0.05% ABV (although the definition differs between countries).

Nonenal Compound that contributes to the cardboard character that develops in stale beer.

Nonreturnable bottles Glass bottles that are not returned to the brewery for refilling; also referred to as "one-trip bottles."

Nucleation Bubble formation in a wort or beer.

Nucleic acids The complex polymeric molecules in living systems that are responsible for carrying the genetic message and translating it.

Organelle A distinct region within a eukaryotic cell with its own specific function.

Organic Refers to compounds containing carbon (apart from carbon dioxide).

Organic acids Carbon-containing acids such as citric and acetic acid released by yeast; are largely responsible for the pH drop during fermentation.

Organoleptic Pertaining to taste and smell.

Original extract The amount of extract present in a starting wort, as calculated from the amount of nonfermented extract left in a beer together with the amount of extract that is equivalent to the amount of alcohol produced in a beer. In some countries this is known as original gravity.

Osmotic pressure The force that drives water to pass from a dilute solution to a more concentrated one through a semipermeable membrane.

Oxalic acid An organic acid found in malt that must be precipitated out in the brewhouse by reacting with calcium to form the calcium salt. Otherwise it will precipitate out in beer as "stone."

Oxidation At its simplest, the process of deterioration of beer due to ingress of oxygen.

Pale ale English-style ale, usually in small pack.

Papain Protein-hydrolyzing enzyme from the paw paw.

Pasteurization Heat-treatment to eliminate microorganisms.

Pentosan Polysaccharide located in the cell walls of barley.

Peptide Molecule consisting of perhaps 2–10 amino acids linked together.

Perlite Volcanic ash used in the filtration of beer as an alternative to kieselguhr.

Pesticides Agents used to protect crops from infection and infestation during growth and storage.

pH A measure of the acidity/alkalinity of a solution.

Piece The bed of grain in a maltings.

Pils A style of lager originating in the Czech Republic.

Pint A measure of beer volume (473 ml in U.S.; 568 ml in U.K.).

Pitching The introduction of yeast into wort prior to fermentation.

Plate-and-frame A type of beer filter.

Plato Unit of wort strength.

Polypeptide A partial breakdown product of proteins containing approximately 10–100 linked amino acid units.

Polyphenol Organic substance originating in the husk of barley and also in hops; can react with proteins to make them insoluble; also known as tannin.

Polysaccharide Polymer comprising sugar molecules linked together.

Polyvinylpolypyrrolidone (PVPP) Agent capable of specifically binding polyphenols and removing them from beer.

Preisomerized extracts Extracts of hops in which the α-acids have been isomerized.

Primings Sugar preparations added to beer to sweeten it or for residual yeast to convert to CO_2.

Propagation Culturing of yeast, from a few cells to the large quantities needed to pitch a fermentation.

Propylene glycol alginate Material added to beer to protect the foam from damage by lipids.

Protease Enzyme that breaks down proteins.

Protein Polymer comprising amino acid units.

Proteolysis The breakdown of proteins by proteases.

Pseudohaze Invisible haze.

Purging Elimination of an unwanted volatile material (e.g., a flavor or a high CO_2 or O_2 content) by bubbling through N_2.

Quality assurance Approach to quality maintenance that involves establishing robust processes and systems that are designed to yield high-quality product.

Quality control Monitoring of a process to generate information that is used to adjust the process in order to ensure the correct product.

Racking The packaging of beer.

Real extract The amount of dissolved material in beer that has not been converted into alcohol.

Reduced hop extracts Preisomerized extracts that have been chemically hydrogenated such that they are no longer light sensitive and can be used to provide bitterness to beers that are intended for packaging in green or clear glass.

Refractometer Device for measuring the strength of beer.

Repitching Practice of taking yeast grown in one fermentation to pitch the next batch of wort.

Resin Substance from hops that generates the bitterness in beer.

Rough beer Beer before filtration.

Saccharomyces cerevisiae Brewers yeast.

Saladin box Type of vessel for germinating barley.

Screening Cleaning of unwanted debris from barley.

Seam The "join" between a beer can and its lid.

Small pack Cans and bottles.

Soluble nitrogen ratio The ratio of the dissolved nitrogen (protein) in wort and the total nitrogen (protein) in malt, which is in direct proportion to the nitrogen modification (sometimes called the Kolbach index).

Sparging Spraying the spent grains with hot water during the wort separation process to facilitate extraction of dissolved substances.

Specification A parameter measured on a raw material of brewing , on a process stream or the finished beer; must be within defined limits for the material to pass to the next stage in the process.

Specific gravity The weight of a liquid relative to the weight of an equivalent volume of pure water (also referred to as relative density).

Spectrophotometer Device for measuring the amount of light absorbed by a solution.

Spent grains The solid remains from a mash.

Spoilage organism Microbe capable of infecting wort or beer.

Square Style of fermenter in that shape.

Stabilization Treatment of beer in order to extend its shelf-life.

Staling Deterioration in the flavor of beer.

Starch Polysaccharide food reserve in barley.

Steely Texture of starchy endosperms in those barleys that are difficult to modify.

Steeping Increasing the water content of barley by soaking.

Sugar Small, sweet carbohydrate.

Sulfur compound Flavor-active material containing sulfur atom(s).

Sweet wort Wort prior to boiling with hops.

Syrup Concentrated solution of sugars.

Taint "Off" flavor in beer or a raw material.

Tannic acid Material added to beer to precipitate out protein.

Tetrazolium Dye used to detect whether barley is alive.

Three-glass test Procedure for "blind" tasting to discern whether two samples of beer can be differentiated.

Tintometer Device consisting of a series of color wheels for comparing with a beer to ascertain whether it has the correct color.

Top fermentation Fermentations in which the yeast collects at the top of the vessel.

Total soluble nitrogen A measure of the dissolved protein in wort.

Trigeminal sense Sensation of pain detected by the trigeminal nerve.

Trub Insoluble material emerging from wort on heating and cooling.

Tunnel pasteurization Pasteurization of small-pack beer by passage through a heated chamber.

Ultrafiltration Filtering out of material at the molecular level by passage through very fine membranes.

Viability Measure of how alive something is.

Vicinal diketones Butterscotch-flavored compounds formed during brewery fermentation.

Vigor A measure of the strength of growth of the barley embryo during germination.

Viscosity A measure of how much a liquid resists flow.

Vitality A measure of the healthiness of a living yeast.

Volatile A molecule in beer that contributes to aroma and is easily driven off.

Vorlauf Recycling of the first wort runnings from a lauter tun in order to ensure "bright" wort.

Water sensitivity Tendency of a barley's germination to be suppressed by the presence of excess water.

Weak wort recycling Use of the weaker worts from the end of wort separation to mash in the next mash.

Whirlpool Vessel for separating trub from boiled wort.

Wort Fermentation feedstock produced in the brewery.

Wort separation Act of separating sweet wort from spent grains.

Xerogel Colloidal stabilizing agent (similar to hydrogel) made from silica.

Yeast Living eukaryotic organism capable of alcoholic fermentations.

Yeast food Source of amino acids and vitamins sometimes used in brewery fermentations.

Zentner Unit of hop mass (50 kilograms).

Notes

1. From Babylon to Busch

Quotations not documented otherwise are taken from C. W. Bamforth, *A Brief History of Beer: Proceedings of the 26th Convention of the Institute of Brewing,* Asia-Pacific Section, Singapore, 2000, pp. 5–12.

1. Delwen Samuel, "Fermentation Technology 3,000 Years Ago—The Archaeology of Ancient Egyptian Beer," *Society for General Microbiology Quarterly* (February 1997), pp. 3–5.
2. J. W. Sykes, "The Indebtedness of Brewers to M. Pasteur," *Journal of the Federated Institutes of Brewing* (1895), pp. 498–525.
3. L. Pasteur, "Memoire sur la fermentation alcohoolique," *Annales de Chimie et de Physique* 58 (1860), pp. 323–426.
4. R. G. Anderson, "Highlights in the History of International Brewing Science," *Ferment* 6 (June 1993), pp. 191–198.

3. Eyes, Nose, and Throat

1. John Taylor, *Ale Ale-vated into the Ale-titude* (1651), as quoted in H. S. Corran, *A History of Brewing* (Newton Abbot, England: David and Charles, 1975), p. 87.

5. The Wicked and Pernicious Weed

1. A. Boorde, *Compendyous Regyment or Dyetary of Health* (London, 1542).

Further Reading

The inclusion of relatively few references in this book has been a deliberate policy, for in most instances the most relevant references are to scientific and technical journals, written for the specialist and unlikely to be readily digested by the layperson. Indeed, most of the books covering the brewing process are somewhat technical; but I here recommend some that will appeal variously to those with different extents of scientific education.

For a basic appreciation of brewing from a more molecular perspective than I have offered in this book, *Brewing* (New York: Kluwer Academic/Plenum Publishers, 2002) by my friend and colleague Emeritus Professor Michael Lewis, together with Tom Young, is the start-off point. A more detailed account is given in C. W. Bamforth, I. Russell, and G. G. Stewart, *Handbook of Alcoholic Beverages,* vol. 1, *Malting and Brewing* (London: Academic Press, forthcoming).

For those in search of much more detail on barley, the volume of choice should be *Barley: Chemistry and Technology,* edited by A.W. MacGregor and R. S. Bhatty (St. Paul, MN: American Association of Cereal Chemists, 1993); for hops, go to R. A. Neve, *Hops* (London: Chapman and Hall, 1991). Yeast is covered extensively by two of my longest and dearest pals in the industry, Chris Boulton and David Quain, *Brewing Yeast and Fermentation* (Oxford: Blackwell, 2001), while two more friends, Denise Baxter and Paul Hughes, address the beer itself in *Beer: Quality, Safety and Nutritional Aspects* (London: Royal Society of Chemistry, 2001). In terms of quality measurements, it would be strange of me not to recommend another of my own offerings, *Standards of Brewing: A Practical Approach to Consistency and Excellence* (Boulder, CO: Brewers Publications, 2002).

H. S. Corran, *A History of Brewing* (Newton Abbot, England: David and Charles, 1975), remains possibly the most instructive historical treatise on brewing.

Index