

What's Your



IBU

By Michael L. Hall, Ph.D.

One of the most important contributions of hops to beer is bitterness. Bitterness provides a counterpart to the sweetness of the malt to create a balanced beer. If you've ever made an IPA that turned out more like a bock, you know that making an accurate estimate of the amount of bitterness imparted by the hops is paramount to success in brewing. This article will compare several methods used to estimate hop bitterness.

The bitterness of hops is derived from the bitter resins in the yellow lupulin glands. These resins, or crystalline weak acids, originally were categorized into alpha-, beta- and gamma-fractions (De Clerck, 1957). The alpha- and beta-fractions are collectively known as the soft resins because they are soluble in hexane. The gamma resin fraction is now referred to as the hard resin fraction because it is insoluble in hexane.

The alpha-fraction is composed of a group of related chemicals called the alpha acids. Alpha acid, often referred to in literature simply as humulone, is comprised of the chemicals humulone, cohumulone, adhumulone, prehumulone and posthumulone (Fix, 1989). Each variety differs only by what is present on a side chain of the humu-

lone molecule. The alpha acids will dissolve in hot wort, up to 250 mg/L at a pH of 5 and a temperature of 212 degrees F (100 degrees C). They are not very soluble in beer, with its lower pH and temperature, and will precipitate out if their concentration is higher than 5 mg/L at a pH of 4 and temperature of 32 degrees F (0 degrees C) (Hough et al., 1982). During the kettle boil, the alpha acids undergo a molecular rearrangement called isomerization. The resultant chemicals are called iso-alpha acids, and there is a corresponding version for each humulone (isohumulone, isocohumulone, etc.). The iso-alpha acids are much more soluble in wort and beer, and they are the primary source of bitterness in beer.

The beta-fraction of the hop resins is composed of the beta acids and many other chemicals, including the oxidation products of the alpha and beta acids that result from aging (De Clerck, 1957). The beta acids are known as lupulones and occur in varieties similar to the humulones. The same side chains of the humulone molecule applied to the lupulone molecule give rise to lupulone, colupulone, adlupulone, prelupulone and postlupulone (Fix, 1989). The beta acids are less soluble than the alpha acids (0.7 mg/L at a pH of 4 and a temperature of 32 degrees F or 0 degrees C) (Hough et al., 1982), but they do contribute some bitterness to beer through their oxidation products. The bitterness from oxidized beta acids, in beer made from aged hops, has been described as an unpleasant bitterness that is not as refined as the bitterness derived from iso-alpha acids (Fix, 1989; Garetz, 1994b).

The hard resins do not contribute to the bitterness of the finished beer.

Quantifying Hop Bitterness

The simplest way to quantify hop bitterness in beer is by specifying the weight of hops added to the wort. Many excellent homebrews have been made with recipes specifying simply "three ounces of hops," but repeating such a success can be difficult. The main problem with this technique is it doesn't take into account the alpha-acid

Finding the solution to balanced beer bitterness is all in the numbers.

CALCULATING BITTERNESS

content of the hops. Alpha acids make up anywhere from 2 to 15 percent of the total weight of the hops, depending on variety. The alpha-acid content can therefore account for a factor of 7 difference in the bitterness level.

Adding alpha-acid content to the calculation allows the brewer to exercise greater control over the bitterness level. The Alpha Acid Unit (AAU) was developed by Dave Line (1985) and adopted by Charlie Papazian (1991) as the Homebrew Bittering Unit (HBU). Both are equal to the weight of the

hops in ounces (W_{oz}) multiplied by the alpha-acid content as a percent (A%):

$$AAU = HBU = W_{oz} \text{ A\%}$$

A recipe calling for 15 AAUs or HBUs needs five ounces of 3 percent alpha-acid hops or two ounces of 7.5 percent alpha-acid hops. Using AAUs/HBUs is better than using only the weight of the hops, but it still allows for wide variations in the bitterness level. There are two main things missing from the formula: the volume of the wort and the boil time. You will achieve a much different bitterness

from 15 AAUs in five gallons than 15 AAUs in 10 gallons. Similarly, 15 AAUs of hops boiled for 60 minutes will impart more bitterness than those boiled for 20 minutes. Many recipes sidestep this problem by specifying the volume and boil time explicitly.

There are, however, still some lurking difficulties with the AAU/HBU method, even if the volume and boil time are given. What does a brewer do if she accidentally boils for 30 minutes instead of 15? What if he can't afford the time to boil for 90 minutes and only boils for 60? What if the total volume of wort cannot be boiled? What if the brewer lives at an elevation of 7,300 feet (like me) where the boiling temperature is lower? In general, how does a brewer estimate bitterness levels under the changing conditions of a homebrewing setup so favorite batches may be duplicated?

The most precise way to define bitterness levels is the International Bitterness Unit, IBU (sometimes referred to as BU). The IBU is defined in terms of the amount of iso-alpha acid actually present in the beer, regardless of how it got there. The definition is:

$$IBU = 1 \text{ ppm of iso-}\alpha\text{-acid,} \\ = 1 \text{ mg of iso-}\alpha\text{-acid/liter of beer.}$$

Assuming the unrealistic circumstance that all of the alpha acids in the hops are converted into iso-alpha acids in the final beer, we can easily calculate the ideal IBU number for a beer as:

$$IBU_{ideal} = \frac{W_{oz} \text{ A\%}}{V_{gal}} \times \frac{7489}{100}$$

The factor of 7489 converts from oz/gal to mg/L, and the factor of 1/100 converts the alpha-acid percent into an alpha-acid fraction. V_{gal} is the volume of the final beer in gallons.

Reality, however, is much more complicated than this simple equation. We will add one more factor to the ideal equation to account for all of the physical processes that make the amount of iso-alpha acids in the finished beer less than the amount of alpha acids added to the kettle. This lumped factor is known as the hop utilization, and will be denoted as a percentage by the symbol "U." Here is the final equation, incorporating another factor of 1/100 for the utilization percent:

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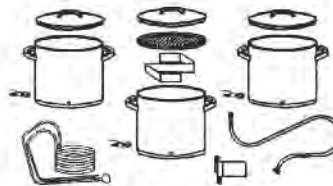
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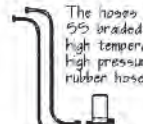
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$$IBU = \frac{0.7489 W_{oz} A\% U\%}{V_{gal}}$$

This is the basic equation all IBU estimation methods use. Everything in this equation is readily available, with the exception of the alpha-acid utilization percent, U%. The only difference between the various IBU estimation methods, which are discussed later, is in the estimation of the utilization percent.

Alpha Acid and Iso-alpha Acid Loss Mechanisms

There are many ways for the alpha acids to go astray on their circuitous path from the lupulin glands of the hops to the iso-alpha acids dissolved in your beer. Each of the loss mechanisms chips away at the utilization percentage until it reaches a value that optimistically peaks at 35 percent. I will discuss the various loss mechanisms in chronological order through the cycle of beer production.

Storage deterioration: The first loss of bitterness potential occurs during hop storage. Before hops even hit the wort, alpha and beta acids are subject to oxidation, but it affects their bitterness in different ways. Oxidation decreases the bitterness of alpha acids and increases the bitterness of beta acids. Some researchers have suggested that the gains and losses in bitterness offset one another, but other studies have shown an overall decrease in perceived bitterness caused by hop deterioration (Rehberger and Bradee, 1975). The amount of alpha-acid deterioration is dependent on age of the hops, storage temperature, hop variety, amount of air present and hop form (pellets or whole cones).

Chemistry: Once the hops make it to the boil, the conversion of alpha acid to iso-alpha acid is imperfect. Instead of isomerization, the alpha acids can be oxidized to make humulinic acids, isohexanoic acid and isobutyraldehyde. There also is a competing form of isomerization, referred to as "reversed" isomerization resulting in anti-isohumulones. The anti-isohumulones, which account for about 10 percent of the isomerization products, are reported to be

twice as bitter as isohumulones (Hough et al., 1982; Fix, 1989).

In addition to the problems associated with undesired chemical pathways, the main isomerization reaction is reversible. In experiments starting with isohumulone in wort, heating resulted in a quasi-equilibrium of 10 to 15 percent humulone, before prolonged heating resulted in turning all of the alpha acids and iso-alpha acids into decomposition products. As a further complication, it appears that the isomerization process can be catalyzed by hop cones, break material or even an inert surface (Hough et al., 1982). A catalyzed reaction will proceed at a different rate, translating into a different utilization percentage. Similarly, the pH of the wort will affect the utilization, with higher pH values leading to higher utilization rates.

Physical separations: At this point the alpha acids have been isomerized and the resultant iso-alpha acids are dissolved in the wort. In the hot wort at the end of the boil the utilization rate is about 50 percent. Physical separation processes now take

over to further limit the amount of bitterness that makes it to your glass. Some of the iso-alpha acids are adsorbed on the surface of the hot and cold breaks and are precipitated out of solution. About 7 percent of the iso-alpha acids are removed with the breaks, irrespective of the amount of the break material. (Hough et al., 1982)

During the fermentation process, iso-alpha acids are scrubbed by the rising CO₂ and collect in the foam of the krausen. This sticky foam can be blown off, skimmed off or stuck on the sides of the fermenter, effectively removing the iso-alpha acids from the finished beer. Iso-alpha acids also are bound up by the yeast cells and removed when the yeast flocculates out. The amount of time the yeast spends in suspension has an effect on the utilization rate of about plus or minus 5 percent. Filtration of the finished beer also will physically remove some iso-alpha acids. (Garetz, 1994b)

Staling reactions: Even when the iso-alpha acids are safely ensconced in the finished beer in your bottle or keg, there can be losses. There are oxidation reactions that

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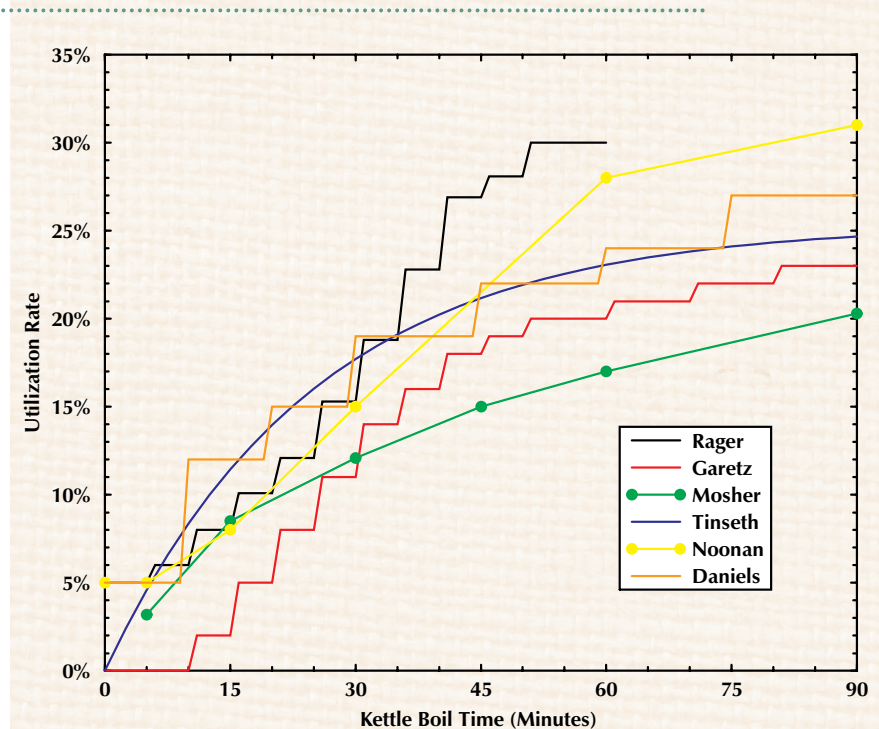
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FIGURE 1. Utilization Rate as a Function of Boil Time

Utilization rate as a function of boil time for wort of SG 1.050, boiled at sea level, using low hopping rates, using fresh leaf hops without a hop bag, with an average yeast flocculation rate, and with no filtration.

can reduce the bitterness of beer over extended storage periods and create “cheesy” aromas in its place.

Problems with Estimating IBUs

There are many difficulties associated with bitterness level estimation. First, all of the processes previously mentioned occur to different degrees and at different rates under the varying conditions of the brew-house. Quantifying their effect on hop utilization can be a challenging task.

With whole leaf hops, variation of alpha-acid content from the measured sample can be a problem. Analyses can vary by as much as 11 percent from bale to bale, and the sampling rate can be as low as one out of every 10 bales. (Hardwick, 1995; Ramsey, 1990) This is less of a problem with pelletized hops because several bales are blended to achieve consistency.

The characteristics of the boil can have a great effect on the rate of hop utilization. The isomerization and solution rate

depend directly on the temperature of the boil, which varies with the altitude of the brewery. How fast and to what extent the iso-alpha acids go into solution depends on the quality of the contact between undissolved iso-alpha acids and unsaturated wort. This is in turn affected by the boil vigor, the boil gravity (via the viscosity) and the hopping rate.

The physical form of the hops also can change the alpha-acid utilization. Pellet hops have been observed to give a greater utilization than loose leaf hops. Several reasons have been postulated: pellet hops disperse more easily in the wort; pellets retain their alpha-acid content during storage better than leaf hops and the pelletization process ruptures the lupulin glands and spreads the resins over the hop particles, giving a larger surface area for isomerization and solution. (Hardwick, 1995; Lewis, 1994)

Even if the level of iso-alpha acids in a beer could be determined exactly, the perception of bitterness can vary greatly. The ionic composition of the brewing water can accentuate hop bitterness; magnesium, carbonate, chloride and sulfate ions all increase

the perception of bitterness (Noonan, 1996; Papazian 1994). Other compounds can cause bitter tastes in addition to iso-alpha acids. These compounds include the oxidation products of beta acids, compounds present in roasted grains and tannins extracted from the grain husks.

Methods of Estimating IBUs

If you ever tell a commercial brewer that you calculated the IBU level in your beer he or she will think you're crazy. The big breweries are very different from homebreweries: they make the same beer over and over again, allowing for modification of the recipe; they can blend different batches to achieve a consistent bitterness level; and they can afford to have the bitterness level of their beers measured often. As a homebrewer, you're probably making lots of different beers, and even when you repeat a beer it's usually a little different from the last time you made it. You can't spend a lot of money analyzing the last batch, and you need to be able to predict the bitterness of tomorrow's batch. Calculation, rather than measurement, is imperative.

But how is bitterness measured? The American Society of Brewing Chemists has adopted a standard method of measurement that involves a centrifuge and a spectrophotometer (1992). Unfortunately, these pieces of equipment are beyond the range of the average homebrewer. You can, however, have your beer measured for bitterness at various laboratories, for example the Siebel Institute of Technology in Chicago, for a fee of about \$40. (Siebel, 1997) Mark Garetz also describes a taste-titration method for estimating IBUs at home using dilutions of iso-alpha extract and your own palate (Garetz, 1994b).

Before we get to the utilization factor estimation techniques, a couple of caveats. First, realize that estimating hop bitterness is a rough science, and it doesn't need to be more exact. The human threshold for detecting bitterness is about 4 IBUs (Kuroiwa et al., 1973), so controlling bitterness levels tighter than that tolerance probably won't be noticed. Also, the processes involved in getting alpha acids from the hops into your

beer involve many steps that are not well known or are hard to quantify. You should evaluate your need for precise bitterness level knowledge and only do as many calculations as you need to satisfy it.

The second caveat is that the following descriptions constitute my versions of the various authors' methods. I have corrected obvious errors in some cases and elucidated confusing areas in others. Sometimes I have even added equations that should have been included by the author. I have tried to remain true to the original works, but you should consult the references if you have any questions.

Simple method: I'll start off with a bare-bones estimation of the IBU level in a beer. For the kettle or bittering hops, which are boiled for an hour or longer, use a utilization of 25 percent. For the flavoring hops, which are boiled for around 10 to 30 minutes, use a utilization of 10 percent. For the aroma or finishing hops (or dry hops), use a utilization of 0 percent. Using the Simple method, the IBU equation becomes:

$$IBU_{kettle} = \frac{18.7 W_{oz} A\%}{V_{gal}}$$

$$IBU_{flavor} = \frac{7.5 W_{oz} A\%}{V_{gal}}$$

$$IBU_{aroma} = 0.$$

Therefore, one ounce of a 1 percent alpha-acid hop in five gallons gives 3.75 IBUs if used for bittering and 1.5 IBUs if used for flavor. This means that, for a five-gallon batch, the Simple method can be used to convert AAUs/HBUs into IBUs:

$$IBU_{kettle} = 3.75 \text{ (HBUs or AAUs),}$$

$$IBU_{flavor} = 1.5 \text{ (HBUs or AAUs).}$$

Boil-time-dependent methods: The rest of the methods discussed in this article give a utilization rate that is a function of the amount of time the hops are boiled. All of the methods apply one or more correction factors to this rate to account for various perturbations to the hop utilization rate. Figure 1 and Table 1 give the utilization percentages for all of the methods, with no correction factors used. These values should be assumed to correspond to a wort of specific gravity of 1.050, boiled at sea level, using

TABLE 1: Utilization Rates (%) as a Function of Boil Time (min.)

Boil Time	RAGER	GARETZ	MOSHER	TINSETH	NOONAN	DANIELS
0.0	5.0	0.0	0.0	0.000	5.0	5.0
2.5	5.0	0.0	1.8	2.414	5.0	5.0
5.0	5.0	0.0	3.5	4.598	5.0	5.0
7.5	6.0	0.0	4.8	6.575	5.8	5.0
10.0	6.0	0.0	6.1	8.363	6.5	12.0
12.5	8.0	2.0	7.4	9.981	7.2	12.0
15.0	8.0	2.0	8.7	11.446	8.0	12.0
17.5	10.1	5.0	9.3	12.770	9.2	12.0
20.0	10.1	5.0	9.9	13.969	10.3	15.0
22.5	12.1	8.0	10.6	15.054	11.5	15.0
25.0	12.1	8.0	11.2	16.035	12.7	15.0
27.5	15.3	11.0	11.8	16.924	13.8	15.0
30.0	15.3	11.0	12.4	17.727	15.0	19.0
32.5	18.8	14.0	12.9	18.454	16.1	19.0
35.0	18.8	14.0	13.4	19.112	17.2	19.0
37.5	22.8	16.0	13.9	19.707	18.2	19.0
40.0	22.8	16.0	14.3	20.246	19.3	19.0
42.5	26.9	18.0	14.8	20.733	20.4	19.0
45.0	26.9	18.0	15.3	21.174	21.5	22.0
47.5	28.1	19.0	15.6	21.574	22.6	22.0
50.0	28.1	19.0	15.9	21.935	23.7	22.0
52.5	30.0	20.0	16.2	22.261	24.8	22.0
55.0	30.0	20.0	16.6	22.557	25.8	22.0
57.5	30.0	20.0	16.9	22.824	26.9	22.0
60.0	30.0	20.0	17.2	23.066	28.0	24.0
62.5	30.0	21.0	17.5	23.285	28.2	24.0
65.0	30.0	21.0	17.8	23.484	28.5	24.0
67.5	30.0	21.0	18.1	23.663	28.8	24.0
70.0	30.0	21.0	18.4	23.825	29.0	24.0
72.5	30.0	22.0	18.7	23.972	29.2	24.0
75.0	30.0	22.0	19.0	24.105	29.5	27.0
77.5	30.0	22.0	19.3	24.225	29.8	27.0
80.0	30.0	22.0	19.6	24.334	30.0	27.0
82.5	30.0	23.0	19.9	24.432	30.2	27.0
85.0	30.0	23.0	20.2	24.521	30.5	27.0
87.5	30.0	23.0	20.5	24.602	30.8	27.0
90.0	30.0	23.0	20.8	24.675	31.0	27.0

low hopping rates, using fresh leaf hops without a hop bag, with an average yeast flocculation rate and with no filtration. The correction factors to account for situations different from these will be discussed in the next major section.

Rager method: Jackie Rager's *Zymurgy's* article (1990) was the first article in the homebrew literature that attempted to estimate hop utilization rates. It still is widely used because of its accuracy and simplicity. His method gives utilization values for different

boiling times as well as a correction factor for boil gravity. No other correction factors are given. The plot has a stair-step form because single values of utilization for ranges of temperatures were given in the original article. (Papazian gives a method for estimating utilization [Papazian, 1991], but his method is an abbreviated version of Rager's method, including the gravity correction, and will not be discussed further here.)

Garetz method: Mark Garetz published a relatively complex method to esti-

CALCULATING BITTERNESS

mate hop utilization rates in his book, *Using Hops*. (1994b) The Garetz method includes a table of utilization values for different boil times, like the earlier Rager method, but the new values are significantly lower than the Rager values. The correction for boil gravity given in the Rager article is used, and new formulas for correction factors for boil temperature and hopping rate are developed. Rough ranges for correction factors for yeast flocculation rate, hop form, hop bags and filtration are given. Also, a formula to predict alpha-

acid loss during storage is given (Garetz, 1994a, b).

Mosher method: Randy Mosher published a method for estimating hop utilization that was based on graphical lookups (Mosher, 1994). Unfortunately, this makes it difficult to precisely determine the utilization percentages, so the values quoted in this article should be assumed to have an error of at least plus or minus 0.1 percent. The Mosher method gives utilization values that are even lower than the Garetz method values for long

boil times. The graphs in the Mosher method give an effective correction factor for boil gravity and hop form.

Tinseth method: As far as I know, Glenn Tinseth has only published his method on the World Wide Web to date (Tinseth, 1997; Pyle, 1997). The Tinseth method is the first to use a formula instead of a graph or table for the relationship between hop utilization and boil time. The Tinseth formula is set up so the boil gravity correction factor is unity at a specific gravity of 1.0557. Modifying it slightly so it is on an equal footing with the other methods (boil gravity correction factor of unity at 1.050), gives this relationship for the utilization rate:

$$U\%_{bt} = 25.367715 (1 - e^{-0.04 t_{boil}})$$

where t_{boil} is the boil time in minutes and $U\%_{bt}$ is the utilization rate that is only dependent on the boil time, the uncorrected rate. Tinseth notes that this curve corresponds to the solution of a chemical first-order reaction. The Tinseth method does not include any correction factors except the boil gravity correction factor. However, the 25.367715 factor in front of the equation represents the maximum value of utilization that can be achieved with extended boiling (at this boil gravity), so a homebrewer easily can modify the equation to fit his or her own circumstances. For long boils, the Tinseth method gives utilization values between the Rager and Garetz methods.

Noonan method: The first mention I've seen of IBUs in the homebrewing literature was in the original edition of Gregory Noonan's *Brewing Lager Beer* (1986). In his recent work Noonan provides a method for calculating hop utilization using tabular values (Noonan, 1996). There are implicit corrections for boil gravity and hop form, in addition to the standard boil time factor. The Noonan method gives utilization values on the high side for long wort boils.

Daniels method: Another recent method was published by Ray Daniels (1996). The Daniels method gives tabular values for utilization rate versus boil time. The boil gravity correction by Rager is included in the method, as is the correction

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for hopping rate from Garetz. Daniels also provides some tables which can be used to scale the utilization rate dependent on the results from laboratory testing.

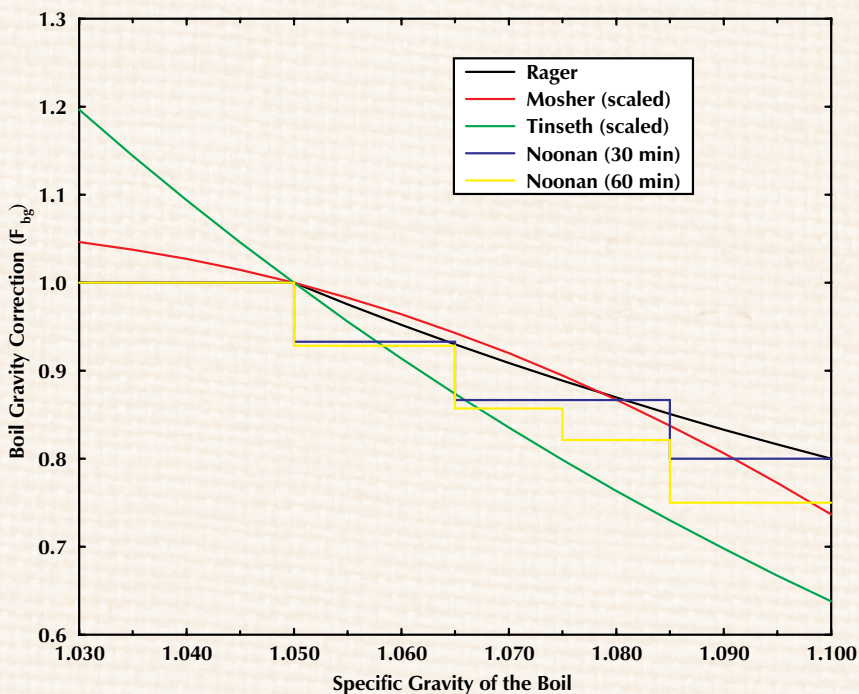
Modifications to the Utilization Factor

The overall utilization rate is the product of the boil time utilization rate (or uncorrected utilization rate) and all of the correction factors:

$$U\% = U\%_{bt} F_{bg} F_{hf} F_{hr} F_{bp} F_{st} F_{hb} F_{yf} F_{fil}$$

where the Fs stand for correction factors for boil gravity, hop form, hopping rate, boiling-point temperature, storage losses, hop bags, yeast flocculation rate and filtration, respectively. All of the F variables are nominally equal to unity, so you may omit any that don't seem necessary to you. Also, because of the way I have structured the formulas, any of the correction factors may be used with any of the other correction factors, and with any of the boil time utilizations given

FIGURE 2. Boil Gravity Correction Factor





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TABLE 2: Boil Gravity Correction Factors

SG_{boil}	RAGER	MOSHER (scaled)	TINSETH (scaled)	NOONAN 30-min.	NOONAN 60-min.
1.030	1.0000	1.0463	1.1969	1.0000	1.0000
1.035	1.0000	1.0379	1.1443	1.0000	1.0000
1.040	1.0000	1.0273	1.0940	1.0000	1.0000
1.045	1.0000	1.0147	1.0460	1.0000	1.0000
1.050	1.0000	1.0000	1.0000	1.0000	1.0000
1.050	1.0000	1.0000	1.0000	0.9333	0.9286
1.055	0.9756	0.9831	0.9561	0.9333	0.9286
1.060	0.9524	0.9642	0.9140	0.9333	0.9286
1.065	0.9302	0.9431	0.8739	0.9333	0.9286
1.065	0.9302	0.9431	0.8739	0.8667	0.8571
1.070	0.9091	0.9200	0.8355	0.8667	0.8571
1.075	0.8889	0.8947	0.7988	0.8667	0.8571
1.075	0.8889	0.8947	0.7988	0.8667	0.8214
1.080	0.8696	0.8673	0.7637	0.8667	0.8214
1.085	0.8511	0.8379	0.7301	0.8667	0.8214
1.085	0.8511	0.8379	0.7301	0.8000	0.7500
1.090	0.8333	0.8063	0.6980	0.8000	0.7500
1.095	0.8163	0.7726	0.6674	0.8000	0.7500
1.100	0.8000	0.7368	0.6380	0.8000	0.7500

in the previous section. First, choose one of the methods to determine the basic boil time utilization (this may be a table lookup). Then, pick and choose which of the following correction factors to apply.

Boil gravity factor: All of the methods employ a boil gravity factor. Figure 2 and Table 2 show the behavior of several boil gravity factor formulas. The most com-

mon formula for this correction was given by Rager:

$$F_{bg} = \frac{1}{1 + 5 (SG_{boil} - 1.050)}$$

where SG_{boil} is the specific gravity of the boil (which may differ from the original specific gravity of the wort). This equation is only used if SG_{boil} is greater than 1.050; other-

wise, F_{bg} is equal to unity. This form for the boil gravity correction factor is used in the Rager, Papazian, Garetz and Daniels methods. The Mosher boil gravity correction factor seems to be based on the Rager method, except it has been fit to a curve to smooth out the rough transition at $SG_{boil} = 1.050$. Mosher only gives his correction factor graphically, but after a little work the form I developed for it is:

$$F_{bg} = 1.0526 [SG_{boil} - 40 (SG_{boil} - 1)^2].$$

The Tinseth method gives another formula for the boil gravity correction:

$$F_{bg} = 1.5673 [(0.000125^{(SG_{boil} - 1)})].$$

I've adjusted both the Mosher and Tinseth formulas so they are equal to unity at $SG_{boil} = 1.050$, which makes them interchangeable with all the other boil gravity factors. Lastly, Noonan only gives his boil gravity factor implicitly in table form, and it varies based on boil time and hop form. I've given a couple of representative curves from his method (30 and 60 minutes for leaf hops) in Figure 2 and Table 2, but if you want to use his method it would be better to consult his tables directly.

From the graph you can see there is a certain amount of agreement. In general, hop utilization rates decrease with increasing boil gravity above 1.050. Below 1.050, Rager and Noonan set the boil gravity factor to unity, while Mosher and Tinseth allow higher values.

Hop form: Correcting the utilization to account for the hop form also is common. Leaf hops or hop plugs do not need a correction, but hops in the pellet form are reported to have an increased utilization. The Garetz method sets F_{hf} equal to 1.1 for pellets boiled from 10 to 30 minutes, and unity otherwise. The Mosher method sets F_{hf} equal to 1.33 for pellets in general, independent of gravity and boil time. Noonan again uses a table, which gives F_{hf} between 1.0 and 1.5 for pellets, with maximum values centering around 15 minutes of boil time and low boil gravities. Daniels does not give a value for F_{hf} , although he recommends using something between 1 and 1.25 for pellets. The other methods do not give a correction factor for hop form, but any of the above methods may be used with them.

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Hopping rate: As more hops are added to the boil, the utilization factor decreases. The Garetz method includes a factor, or rather an equation, to account for this:

$$F_{hr} = \frac{1}{1 + (V_{final}/V_{wort})(IBU/260)},$$

where V_{final} is the final volume of the beer (the same as V_{gal} above), V_{wort} is the volume of wort in which the hops are boiled, and IBU is the number of IBUs extracted from the hops. Garetz suggests that an iterative procedure should be used because this factor includes the IBU value that is unknown at the start of the calculation. However, placing this factor into the original formula,

$$IBU = \frac{0.7489 W_{oz} A\% U\%*}{V_{gal}} \left[\frac{1}{(V_{gal}/V_{wort}) IBU/260 + 1} \right],$$

where $U\%*$ is $U\%$ with all the factors except F_{hr} (i.e. $U\%* = U\% / F_{hr}$), we can see this is a quadratic equation in IBU. Quadratic equations can be solved easily to obtain:

$$IBU = \frac{130 V_{wort}}{V_{gal}} \times [-1 + \sqrt{1 + 0.0115215 W_{oz} A\% U\%*/V_{wort}}].$$

Note that the hopping rate factor calculation must be the last calculation, after all the other factors have been determined. The Daniels method is the only other method that includes a hopping rate factor, and he quotes the Garetz method, using the iterative solution procedure instead of the quadratic procedure given here. The hopping rate factor is a function of the boil time utilization rate and all of the other correction factors, so it will change when they are modified. The hopping rate factor could be applied to any of the methods.

Boiling-point temperature: The isomerization reaction rate depends on temperature, so the boiling-point temperature at your elevation can make a big difference. At my elevation, 7,365 feet, water boils at 198 degrees F (92 degrees C) instead of 212 degrees F (100 degrees C). Garetz gives a correction factor for this effect:

$$F_{bp} = \frac{1}{1 + E_{ft}/27500},$$

where E_{ft} is the elevation in feet. None of the other methods correct for boiling-point temperature.

Storage losses: The alpha acids in hops deteriorate over time, reducing the bittering power of the hops. It is unclear whether or not the gain in bitterness from the oxidation of the beta acids offsets this effect to the extent that no correction is necessary. The best solution for the homebrewer is to buy only fresh hops in vacuum-sealed bags and store them in a freezer for less than three

months before use. If you do want to calculate the storage losses, Garetz (1994a, b) provides a formula for the correction factor:

$$F_{st} = e^{-k M_t M_{st} t_{st}},$$

where k is the base rate constant, M_t is a modification factor for the storage temperature, M_{st} is a modification factor for the type of storage and t_{st} is the storage time in months. M_t is given by

$$M_t = 2^{(T-20)/15},$$

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where T is the storage temperature in Celsius. M_{st} is unity for hops exposed to air (either unsealed or in polybags), 0.75 for hops stored in airtight but oxygen-permeable containers, and 0.5 for vacuum-packed hops or hops stored under nitrogen or carbon dioxide. The base rate constant, k, is dependent on the hop variety and can be calculated from either the Hop Storage Index (HSI) or the “% Loss” value for the hop variety, which you can get from your hop supplier or from Garetz (Garetz, 1994a, b). If you start with the HSI, first calculate

$$\%Loss = 110 \log (HSI/0.25),$$

which is actually the fraction (not the percent) of alpha acids lost during storage at 68 degrees F (20 degrees C) for six months. Now that you know the “%Loss,” the base rate constant is given by

$$k = -\ln (1 - \%Loss)/6.$$

This corrects an error in the original work and is somewhat simpler.

Other factors: There are many other factors that affect the iso-alpha-acid utilization in beer, but most of them are very hard to quantify. The only method that even attempts to quantify any other effects is the Garetz method.

Garetz recommends $F_{hb} = 1.0$ for hops loose in the boil, $F_{hb} = 0.9$ for hops in a hop bag, and $F_{hb} = 0.8$ for hops in a hop bag stuffed full. A yeast flocculation rate factor (F_{yf}) of 0.95 is recommended for slow flocculation, 1.0 for average flocculation and 1.05 for fast flocculation. The filtration factor (F_{fil}) varies from 1.0 for no filtration to 0.975 for aggressive filtration.

A Sample Calculation

For this article I brewed a batch of my standard hoppy pale ale (Jemez Pale Ale 5, a.k.a. More Hops, Daddy!) and had the bitterness level measured by the Siebel Institute. This beer was brewed with the following characteristics:

Batch size: 11.5 gal (full boil)

Boil gravity: 1.057

Hop schedule: (all English Goldings at 5.1% alpha acid)

- 5 oz (60 min.)

TABLE 3: Sample Beer Utilization Correction Factors

METHOD	F_{bg}	F_{hf}	F_{hr}	F_{bp}	F_{st}	F_{hb}	F_{yf}	F_{fil}	Product
SIMPLE	1	1	1	1	1	1	1	1	1
RAGER	0.9662	1	1	1	1	1	1	1	0.9662
GARETZ	0.9662	1	0.9227[1]	0.7888	0.8881	1	1.05	1	0.6558
MOSHER	0.9758	1	1	1	1	1	1	1	0.9758
TINSETH	0.9390	1	1	1	1	1	1	1	0.9390
NOONAN	0.9286[2]	1	1	1	1	1	1	1	0.9286
DANIELS	0.9662	1	0.8842[3]	1	1	1	1	1	0.8543

[1] 20 min. = 0.9911.

[2] 30 min. = 0.9333, 15 min. = 1.0, 5 min. = 1.0.

[3] 20 min. = 0.9655, 5 min. = 0.9880.

- 2 oz (20 min.)
- 2 oz (five min.)
- 4 oz (dryhopped for five days)

%Loss: 0.45

Storage: Hops were used in the springtime, right after receiving them via mail order, so assume hops were stored at 32 degrees F (0 degrees C) for four months in airtight bags at the supplier.

Hop form: plugs

Hop bags: no

Filtration: no

Elevation: 7,365 ft.

Yeast: Wyeast No. 1968 Special London Ale

Flocculation: high

Table 3 shows the calculated utilization correction factors for this beer for all of the methods. With the exception of the Simple method, all of the methods include a boil gravity correction. Most of the methods include a correction for hop form, but this beer only used plug hops, so no correction was necessary. The Garetz and Daniels methods include a hopping rate calculation, and the rest of the corrections are the sole

province of the Garetz method. Note that the product of correction factors is much lower for the Garetz method.

Combining the correction factors with the boil time utilization factors from Table 1 and using the IBU equation gives the estimates for the IBUs of the sample beer shown in Table 4, which range from 24 to 57. The actual bitterness, as measured by Siebel, was 45.5 IBUs.

So what does this mean? Are some methods better at predicting bitterness than others? Keep in mind this is only a single data point, and there are many intangibles in the brewing process that can affect the bitterness level. Some methods may be better for certain brewers. Justifications aside, three of the methods came very close to the mark: Tinseth, Daniels and, surprisingly, the Simple method. The Simple method worked well because the beer was close to an average brew; the correction factor product was close to unity. The Tinseth and Daniels methods have similar boil time utilization factors (see Figure 1) and correction factors

TABLE 4: Sample Beer IBUs

METHOD	60 min.	20 min.	5 min.	5 day	TOTAL
SIMPLE	41.52	6.64	0	0	48.16
RAGER	48.13	6.48	3.21	6.42[1]	57.82
GARETZ	21.78	2.34	0	0	24.12
MOSHER	27.55	6.03	2.07	0	35.65
TINSETH	35.97	8.71	2.86	0	47.54
NOONAN	43.18	6.71	3.32	6.64[1]	53.21
DANIELS	34.05	9.29	3.17	0	46.51

[1] Even though Rager and Noonan specify a utilization rate of 5 percent for hops that are not boiled, I don't think they meant to include dry hops, so these values are left out of the totals. Daniels specifically states a utilization of 0 percent for dry hops.

CALCULATING BITTERNESS

that pull them closer to each other – and to the measured value.

The Garetz method, which didn't fare as well, started out with lower boil time utilization values than most of the other methods and was pulled down even further by the low correction factor for boil temperature because I brew at a high altitude. The Mosher method, which has the lowest boil time utilization numbers, was somewhat higher than the Garetz estimate because it had a high correction factor product. The Rager and Noonan methods both came in on the high side, which could have been predicted because their boil time utilization curves are the highest.

So which method should a homebrewer use? I recommend brewing a batch as close to your normal procedure as possible, and taking good notes. Then, send a beer off to be analyzed. Calculate the bitterness using all of the methods to determine which one fits your brewing style best. If you want to, mix and match the formulas (in this article only) to use your favorite boil time utilization curve with your favorite correction factors.

Designing a Recipe

How does one go about determining the hop bill for a new recipe? First, decide on the hop varieties you will use for bittering,

flavor, aroma and dry hops according to style or personal preference. Then check with your hop supplier to see what the alpha-acid percentages are for your chosen varieties. Once again, use personal preference or the requirements of the style to set the amount of flavor, aroma and dry hops. Calculate the bitterness contributed by the flavor and aroma hops and subtract this from the overall desired bitterness level. Finally, work backwards to determine the weight of bittering hops to add to your brew.

A Glimpse Ahead

In this first article I have given a survey of the methods available in the homebrewing literature for estimating the hop bitterness level in beer. In a future article I will develop a new method for bitterness estimation based on research I am doing in the professional brewing literature. I hope you will be able to enhance your brewing process with the formulas contained in this article.

Nomenclature

AAU Alpha Acid Unit, = $W_{oz} A\%$

A% alpha acid content as a percentage

E_{ft} elevation or altitude in feet

F_{bg} hop utilization rate correction factor for boil gravity

F_{bp} hop utilization rate correction factor for boil point temperature

F_{fil} hop utilization rate correction factor for filtration

F_{hb} hop utilization rate correction factor for hop bags

F_{hf} hop utilization rate correction factor for hop form

F_{hr} hop utilization rate correction factor for hopping rate

F_{st} hop utilization rate correction factor for storage losses

F_{yf} hop utilization rate correction factor for yeast flocculation rate

HBU Homebrew Bittering Unit, = $W_{oz} A\%$

HSI Hop Storage Index

IBU International Bitterness Unit, = 1 ppm of iso-alpha acid = 1 mg of iso-alpha acid / liter of beer

IBU_{aroma} IBU number contributed by the aroma hops

IBU_{flavor} IBU number contributed by the flavoring hops

IBU_{ideal} IBU number for a beer assuming 100% utilization (not realistic)

IBU_{kettle} IBU number contributed by the kettle or bittering hops

k base rate constant for bitterness loss during storage

%Loss fraction (not percent) of alpha acids lost during storage at 68 degrees F (20 degrees C) for six months

M_{st} a modification factor to the storage loss rate for the storage type

M_t a modification factor to the storage loss rate for the storage temperature

SG_{boil} specific gravity of the boil, which may differ from the original specific gravity of the wort

t_{st} hop storage time in months

U% hop utilization rate as a percentage

$U\%_{bt}$ hop utilization rate (as a percentage) that is only dependent on the boil time; the uncorrected rate

$U\%^*$ hop utilization factor, U%, with all the factors except F_{hr} ; i.e. $U\%^* = U\% / F_{hr}$

V_{final} final volume of beer in gallons, = V_{gal}

V_{gal} final volume of beer in gallons, = V_{final}

V_{wort} volume of wort that the hops are boiled in, in gallons

W_{oz} weight of the hops in ounces



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T hop storage temperature in Celsius
 t_{boil} boil time in minutes

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