Very High Gravity Brewing—Laboratory and Pilot Plant Trials

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ABSTRACT

Transfer to the brewing industry of laboratory-scale, very high gravity (VHG) fermentation technology resulted in a series of experiments that have shown, under pilot plant conditions, that worts up to 24°P can be fermented within acceptable time frames to produce beers with more than 11% (v/v) ethanol. Freshly harvested commercial pitching yeast slurry was used in all cases. Extensive chemical analyses and sensory evaluation indicated that the beers, after dilution to 5% ethanol, were cleaner and more physically stable than control beers. Ester levels in the VHG beers were elevated, but after dilution, the concentrations were comparable to those of commercial products. Organoleptically, beers in the 18–20°P range were preferred by most taste panelists.

Keywords: Analyses, FAN, Fermentation, HG, Sensory, VHG

In the past, traditional brewing has been performed by fermenting worts of 11–12°P to produce beers of 4–5% (v/v) ethanol. By increasing the wort gravities from 12 to 18°P (high gravity brewing), substantial savings can be realized by the brewer (2,8,14,28). Plant efficiency and capacity are increased; reductions in labor, energy, and capital costs are realized; beer flavor and physical stability are improved; and more ethanol per unit of fermentable extract is recovered (2,8,14,21,28). For example, it has been estimated that an increase in wort gravity from 12 to 15°P results in a lowering of energy consumption by as much as 14% and an increase in manpower productivity of 25–30% (14). Yeast crop has not been found to increase in proportion to increases in gravity (13,21). As a result, the ethanol yield per degree Plato of fermentable extract is raised. More fermentable extract is metabolized to ethanol rather than used to produce cell mass (2,21,28). Higher pitching rates are required, however; recommended rates are $1–2 \times 10^6$ cfu/ml per °P (2,5).

Beers produced by high gravity brewing are reported to have extended physical and flavor stability (2,21,23,27). These improvements have been attributed to increased precipitation of high molecular weight material, higher alcohol concentration, and increased concentrations of proteins and polyphenols in solution (28). More rapid and complete precipitation occurs in the fermentor, reducing the levels of nonbiological haze during storage (28).

High gravity (HG) beers do not taste the same as conventionally brewed beers (21). An increase in the acetate esters (21,23,27,28) contributes a smoothness and palate balance. The higher esters, however, affect the flavor profile characteristic of regular gravity beers. Casey et al (3) indicated that after dilution of very high gravity (VHG) lager beer to normal alcohol levels, ester levels resembled those in commercially produced lager beers.

Attempts to ferment worts above 18°P (13,14) under VHG conditions have proven difficult unless attention is given to yeast nutrition (2,7,8,16). Yeast crop viability and stuck or sluggish fermentation rates have been experienced with VHG, and even HG, worts. The inability of the yeast to ferment wort normally has been blamed on ethanol toxicity (6,26) and high osmotic pressure (20,23).

With normal 12°P wort, a minimal requirement of 160 mg of free amino nitrogen (FAN) per liter of wort has been found necessary for proper fermentation to occur (6). However, publications by Casey et al (7,8) indicated that fermentation difficulties of HG and VHG worts arise because of nutritional deficiencies, most notably FAN and oxygen. When such deficiencies have been remedied, worts over 32°P have been fermented using commercial brewing yeast slurry (4); dogma indicating that brewer's yeasts are tolerant to only 7–9% ethanol has now been disproved (5,6). Final alcohol values in these beers as high as 16.4% (v/v) have been reported, an amount far exceeding the published tolerance limits of brewer's yeasts (11,15,22). With VHG technology, all of the advantages of HG brewing are realized, and even larger economies of scale may be possible. In addition, a number of potential bacterial contaminants are suppressed (17).

The objectives of the current study were to ferment VHG high adjunct worts at gravities of interest to brewers (up to 24°P), determine in pilot scale the requirements of commercial lager yeast for added yeast food, and evaluate, organoleptically and analytically, the beer produced.

MATERIALS AND METHODS

Bench-Scale Fermentor Trials

Bench-scale fermentations were conducted in 1- or 2-L Celstir fermentors (Wheaton Scientific, Millville, NJ). Temperature was maintained at 14°C using a Haake D-3G circulator (Haake Inc., Saddle Brook, NJ). Stirring, when used, was provided at 90 rpm. All-malt wort from a production facility was sterilized with diethylpyrocarbonate (0.1%, v/v) when received. When required, wort was diluted to 12°P, and appropriate aliquots of pasteurized (1 hr, 70–75°C) Casco 1639 high maltose syrup (Canadian Starch Co., Montreal) were added to achieve the desired initial gravities. Casco 1639 contains 80–82% dry solids, of which carbohydrates of degree of polymerization (DP) 1 account for 6–14% (dry basis), DP 2 carbohydrates account for 50–58%, DP 3 carbohydrates for 11–21%, and DP 4 and above for 18–22%.

When yeast foods were added, final worts were again "cold-sterilized" with diethylpyrocarbonate (0.1%, v/v, 24 hr at 2°C). Gist Brocades AYE 2200 yeast food (an autolysed yeast product also known as AYE Light, now obtainable from Gillette Foods Inc., Larteret, NJ) was used along with other selected varieties of yeast foods (16). Although the exact composition of this yeast food is proprietary, it has been shown to contain high levels of FAN and low inorganic ions (16). Worts were oxygenated to approximately 7 mg/L before inoculation. Commercial *Saccharomyces cerevisiae* lager yeast was obtained in slurry form from

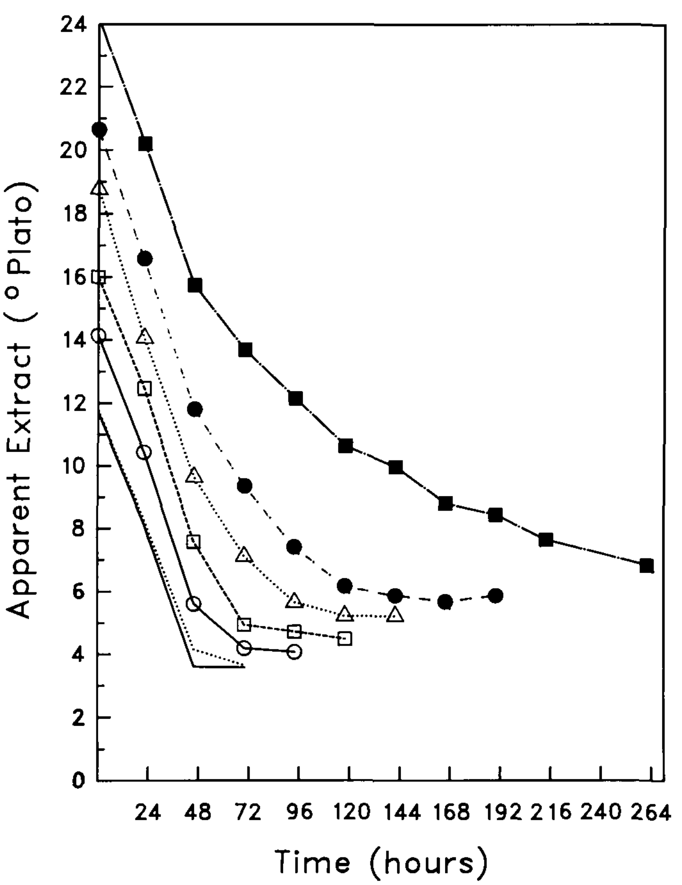

Fig. 1. Assessment of fermentability of produced very high gravity (VHG) worts in bench-scale fermentations. Solid line = 12°P; dotted line = 12°P with anaerobic incubation; ○ = 14.2°P; □ = 16.2°P; △ = 18.2°P; ● = 20.0°P; ■ = 24.0°P.

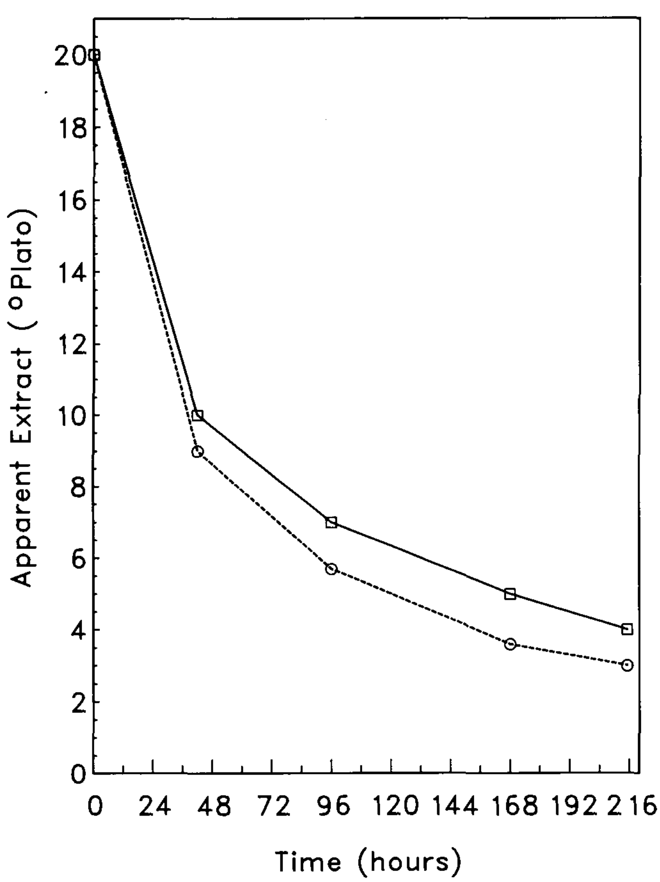

Fig. 2. Effect of addition of yeast extract on wort apparent extract (EBC fermentor). □ = Control; ○ = yeast extract.

production and pitched at 10–15 million cfu/ml based on slurry dry weight.

Wort gravity was determined in degrees Plato by gravimetric methods (4). FAN was determined by the EBC ninhydrin method (1,12). Ethanol was measured enzymatically using alcohol dehydrogenase (24).

EBC-Style Fermentor Trials

Key experiments from bench-scale studies were confirmed using 3-L EBC-style fermentors (19). The fermentations were monitored daily for apparent extract, alcohol, and yeast in suspension. At-end fermentation yeast crop volume was determined.

Pilot-Scale Fermentations

Brewing in the pilot plant involved the production of eight separate 35-L worts over a three-day period. All brews were produced from two-row Harrington malt, Casco 1639 syrup, and hops. Constituents were varied to ensure a 12°P all-malt base, and the appropriate amount of Casco syrup was added to poise the worts at the desired gravity as follows: 12°P, 5.5 kg of malt, no adjunct; 18°P, 5.5 kg of malt, 2.38 kg of syrup; 20°P, 5.5 kg of malt, 3.19 kg of syrup; and 24°P, 5.5 kg of malt, 4.84 kg of syrup. When yeast food was required, 1.5 g/L of AYE 2200 was added to the kettle before knock-out.

All worts were pitched with production lager yeast slurry stored at 2–3°C until needed. Pitching rates were set at 12.5 million cells per milliliter with an oxygenation rate of 10 mg/L. When the fermentations were completely attenuated, the beer was dropped to cold storage at 1°C and held for two weeks. The beer then was diluted to 5% (v/v) ethanol with dilution water obtained from the brewery, filtered, and bottled. The final beers were subjected to full analytical evaluation.

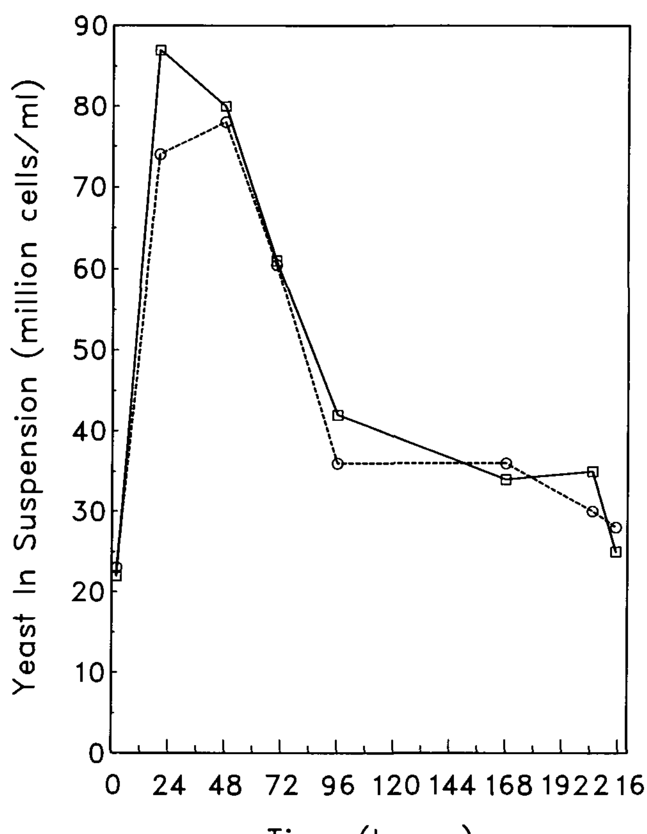

Fig. 3. Effect of addition of yeast extract to wort on yeast in suspension (EBC fermentor). □ = Control; ○ = yeast extract.

Analytical Methods

Free α-amino acid nitrogen values (1,8) were measured at zero time and at the end of fermentation. All other analyses were performed daily. Density and alcohol were determined using the Anton Paar DMA-55 (Anton Paar KG, Graz, Austria) and a Carl Zeiss refractometer. Yeast in suspension was determined by hemacytometer (1) and by standard plating (1) onto universal beer agar. Yeast viability was determined by staining (18) using eosin-y and by plating onto universal beer agar (1). Microbiological contaminants were monitored by plating serial dilutions onto universal beer agar containing 10 μg/L of cycloheximide.

Carbohydrates were analyzed by high-performance liquid chromatography using the method described by Dadic and Belleau (10), and volatiles (esters and fusel alcohols) were quantitated by the cryogenic headspace technique described by Chen (9).

Flavor evaluations were conducted using a randomized complete block design (25). Each sample was tasted three times and tasted against every other sample once. Nine expert taste panelists evaluated the beers in six sessions held over a four-day period. Results were statistically analyzed by ANOVA (25), which was routinely used for collaborative sensory analysis.

RESULTS

Bench-Scale Fermentations

Bench-scale experiments, conducted with commercial all-malt lager wort containing FAN (180–190 mg/L) and adjusted to a

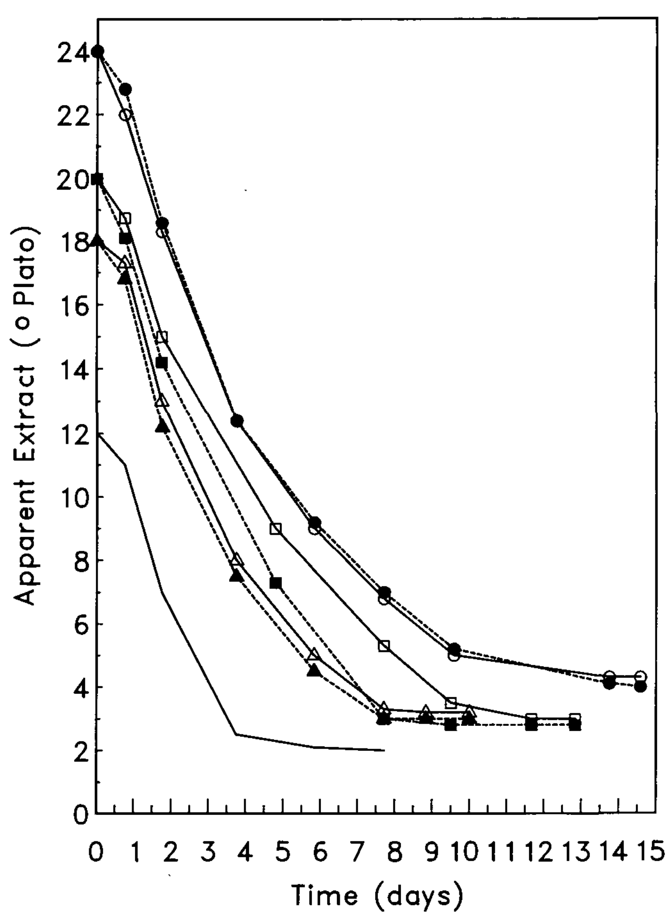

Fig. 4. Apparent extract of pilot brewery very high gravity (VHG) fermentations. ○ = 24°P without yeast food; ● = 24°P with yeast food; □ = 20°P without yeast food, ■ = 20°P with yeast food; △ = 18°P without yeast food, ▲ = 18°P with yeast food; solid line = 12°P control without yeast food.

range of gravities from 12 to 24°P with brewer's syrup, all fermented to completion. All worts to 20°P fermented within normal time frames at 14°C using commercial lager yeast (Fig. 1). Only the 24°P wort fermentation required more than six to seven days to fully ferment under the described conditions. In supplementary experiments, the 24°P wort was shown to require more FAN (550 mg/L added, of which more than 200 mg/L was usable) to allow complete fermentation to be achieved within the six-day fermentation period (*data not shown*). In FAN-supplemented 24°P wort, under these conditions, more than 9.2% (w/v) (>11.7%, v/v) alcohol was produced. Previously in this laboratory, fermentations of VHG worts over 32°P have yielded beers up to 16.4% (v/v) alcohol (2,8).

Worts over 18°P appeared to require FAN (at least 280 mg/L) to enable adequate fermentation to proceed. FAN levels above 280 mg/L increased the fermentation rate. Evaluation of several yeast foods for supplementation of FAN to wort showed that autolyzed yeast extract (Gist-Brocades AYE-2200) performed better than yeast foods containing high levels of inorganic ions or proteins and/or ammonium salts. This confirmed previous findings (16).

Also, it was shown that a nonflocculent *S. cerevisiae* (CFCC 29) yeast or a less-flocculent variant of the production lager yeast was necessary if laboratory fermentations were conducted without stirring. The use of a less-flocculent production lager yeast eliminated the sluggish fermentation profile experienced with normal flocculent varieties of the same yeast.

Fermentations in EBC-Style Fermentors

The key experiments conducted at bench scale at the University of Saskatchewan were duplicated in 3-L EBC-type fermentors. This was done to determine whether scale-up problems were going to be encountered before full pilot brewery-scale trials.

Commercial lager yeast was able to ferment all of the worts from 12 to 24°P original gravity in EBC-style fermentors. However, the requirement for additional FAN, necessary to provide faster fermentation at higher gravities in bench-scale trials, was not as pronounced in the 3-L scale fermentations (20°P wort shown with and without yeast food in Fig. 2). This was attributed to the abnormally high levels of FAN (up to 240 mg/L) found in the pilot brewery worts produced for this phase. Because of the high FAN levels in this basal wort, supplementation of these worts with yeast food did not significantly increase the rate of fermentation or result in better attenuation. Moreover, the addition of FAN did not lead to an increase in the yeast crop recovered or an increase in the levels of yeast cells in suspension throughout the fermentations (20°P wort shown in Fig. 3). Fermentations at this stage were successful and further scale-up to the pilot brewery was justified.

Pilot Brewery Trials

Brewing. The pilot brewery consists of a 50-L mash mixer, lauter tun, kettle, and batch wort cooler. The basic brewhouse was modified from an original Zieman brewhouse. It was engineered to produce wort under conditions as close to production scale as possible. No irregularities were noted during the brewing procedures; normal conversion, runoff, and kettle evaporation levels were recorded.

Fermentation

Wort gravity reduction during the fermentation (Fig. 4) indicated that the effect of yeast food addition was minimal. All VHG worts fully attenuated. An examination of the FAN in the worts (Table I) showed that the addition of yeast food increased the FAN levels by approximately 32%. However, worts that were not supplemented with yeast foods again contained abnormally high FAN, averaging 276 mg/L (Table I). As a result, residual FAN levels left in the beers also were elevated (Table I). Only at 20°P did the addition of Gist-Brocades AYE light yeast food increase the rate of attenuation. At 18 and 20°P, fermentations

TABLE I
Free Amino Nitrogen (FAN) Concentrations (mg/L) in Pilot Brewery Very High Gravity Worts/Beers

Gravity (°P)	Wort	Beer	FAN Utilization (Difference)
12°P control	272	192	80
18°P	275	122	153
18°P + yeast food	369	245	124
20°P	288	187	101
20°P + yeast food	350	260	90
24°P	269	128	141
24°P + yeast food	375	225	150

TABLE II
Real Degrees of Fermentation of Very High Gravity Pilot Plant Worts

Gravity (°P)	Real Degree of Fermentation (%)
12°P control	67.9
18°P	68.1
18°P + yeast food	68.1
20°P	68.0
20°P + yeast food	67.6
24°P	68.6
24°P + yeast food	68.4

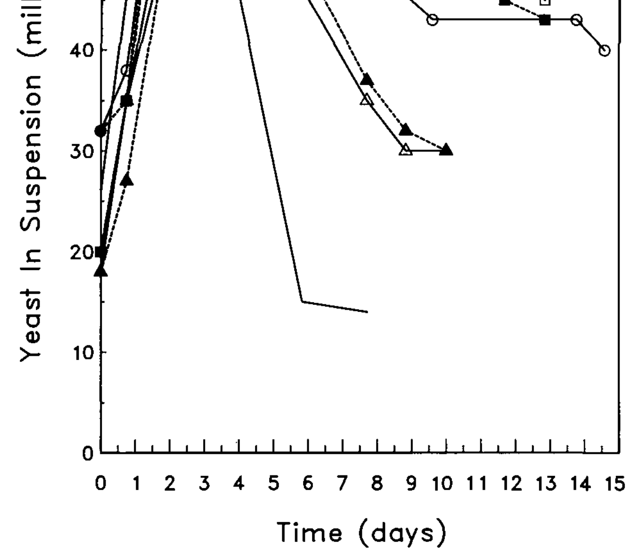

Fig. 5. Yeast in suspension profiles of pilot brewery very high gravity (VHG) fermentations. ○ = 24°P without yeast food; ● = 24°P with yeast food; □ = 20°P without yeast food, ■ = 20°P with yeast food; △ = 18°P without yeast food, ▲ = 18°P with yeast food; solid line = 12°P control without yeast food.

with the normally flocculent lager yeast reached final attenuation within 11 days. Fermentation of 24°P wort required an additional four days. The real degree of fermentation of all trial fermentations (Table II) was similar, averaging close to the current production values (67–70%).

Plots of the yeast cells in suspension during the fermentations (Fig. 5) were similar to plots obtained at lower, more regular wort gravities. Although at 24°P, the fermentation supplemented with yeast food contained higher yeast cell numbers in suspension near the end of fermentation than the unsupplemented fermentations (subsequent work with high FAN worts did not verify this difference), the recovered yeast crops (Table III) in other fermentations were not significantly higher when supplemented. It was noted, however, that as original wort gravity increased, the number of yeast cells remaining in suspension at the end of fermentation increased (Fig. 5). Yeast viabilities at the end of fermentation were similar for all fermentations.

Ethanol production at higher gravities (Table IV) increased as the original wort gravity was raised. The addition of yeast food did not significantly affect final ethanol production. At the highest gravity examined in these trials, 24°P, the final ethanol content was 11.2% (v/v).

Two key volatile components, total fusel alcohol and ethyl acetate, were determined at the end of fermentation (Fig. 6). Ethyl acetate was unchanged as the wort gravity increased. Fusel alcohol levels were elevated at the higher wort gravities, but after dilution of the beers to 5% (v/v) ethanol, the levels were comparable to those of the control (Fig. 7).

Carbohydrate concentrations during fermentations increased as the original wort gravity increased (Fig. 8), however, the proportional ratio of each sugar remained constant.

Before dilution, the beers were evaluated for a number of parameters (Table V). Final apparent extracts rose as the original gravity of the worts increased. This was predicted based on similar real degree of fermentation values for all gravities (Table II). Real extracts increased as the original gravity values of the trials increased because of the elevated apparent extracts and alcohol concentrations (Table V). The color of the produced VHG beers declined as original gravity increased, caused by additional dilution by elevated adjunct levels. The pH values and vicinal diketone concentrations were virtually unchanged as the original gravity levels varied (Table V). SO_2 concentrations decreased as the original gravity increased.

TABLE III
Yeast Crop Recovery[a]
from Very High Gravity Pilot Plant Fermentations

Brew	Yeast Recovery Ratio[b]
12°P control	1.58
18°P	1.75
18°P + yeast food	1.82
20°P	2.57
20°P + yeast food	2.73
24°P	1.55
24°P + yeast food	1.78

[a] Includes yeast cells remaining in suspension.
[b] Ratio = yeast cell volume recovered at end of fermentation (cells per milliliter × volume in liters)/yeast cell volume pitched (cells per milliliter × volume in liters).

TABLE IV
Final Ethanol Concentrations
from Very High Gravity Pilot Brewery Fermentations

Gravity (°P)	Ethanol (%, v/v)
12°P control	5.0
18°P	8.30
18°P + yeast food	8.32
20°P	9.50
20°P + yeast food	9.42
24°P	11.2
24°P + yeast food	11.1

Analyses of Finished Beer

Analytical. The pH values of the diluted beers made from all of the trial brews were found to be high (Tables VI and VII). The beer from the control all-malt brews at 12°P had a final pH of 4.64, while the diluted beer from 24°P worts had a pH of 4.91. This was attributed to increasing dilution with water of high alkalinity.

As the original wort gravity increased, the beer color, SO_2 content, and foam values decreased (Tables VI and VII). This was caused by the corresponding increase in dilution required to produce a final product of 5% (v/v) ethanol. The reduction in beer color also was attributed to the increased adjunct ratios.

Elevated physical stability of the beer was noted as the original wort gravity was raised. This is indicated by decreased five-day formazin turbidity unit values (Tables VI and VII). All values for residual fermentable extract were within specification (<0.2°P) (Tables VI and VII).

Organoleptic. Organoleptic evaluations of the beer revealed that there was a significant difference between the very high gravity beers and the 12°P control beer (Table VIII). The beers were divided into two distinct groups. The 18 and 20°P samples and the 24°P sample with yeast food were rated significantly higher overall than the control, the 18°P sample with yeast food, and the 20°P sample with yeast food. The four most highly rated

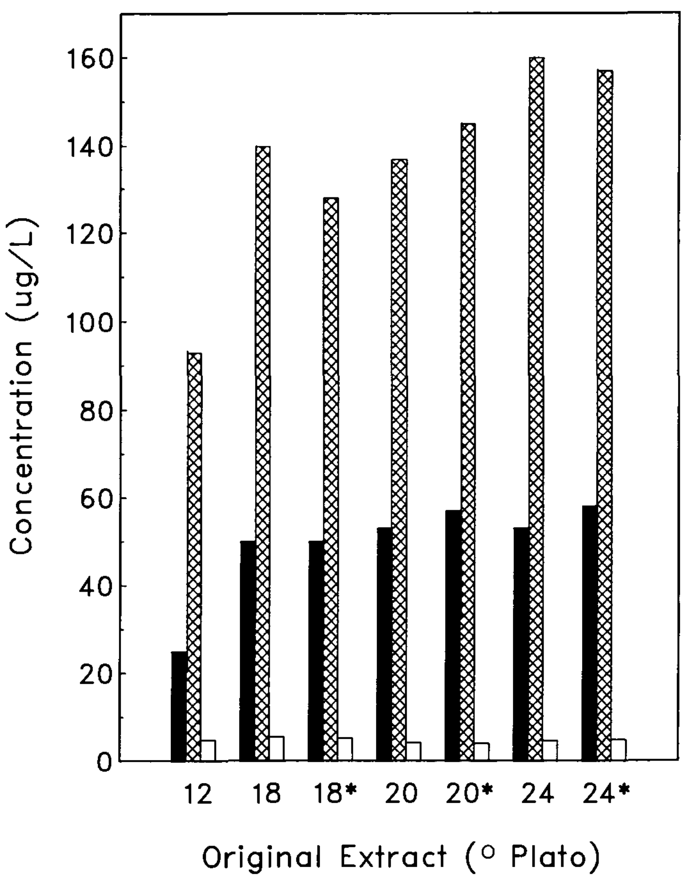

Fig. 6. Concentration of ethyl acetate, fusel alcohols, and isoamyl acetate before dilution to 5% (v/v) alcohol. Asterisk indicates added yeast food. Solid bar = ethyl acetate; patterned bar = fusel alcohols; clear bar = isoamyl acetate.

samples were also preferred in the same order, whereas the 18°P with yeast food, the 20°P with yeast food, and the control were preferred fifth to seventh, respectively. Under VHG conditions, at all three gravities, beers without yeast food were preferred and rated higher than those with yeast food added. Certainly, with the high original wort FAN values present in these worts, additional FAN in the form of yeast extract would not be necessary. Little benefit was gained under these pilot scale conditions by FAN addition.

DISCUSSION

Recent studies (2,5–8) have indicated that at original wort gravities above 18°P (VHG fermentation), proper oxygenation and additional FAN over suggested levels of approximately 160 mg/L are required for adequate attenuation. Preliminary bench-scale trials with commercial wort and commercial lager yeast confirmed this fact. Analysis of the bench-scale worts for FAN revealed that at all of the gravities, the FAN levels exceeded the minimal requirements of 160 mg/L FAN (8), but this was not enough FAN to prevent a FAN supplement from benefitting the rate of fermentation as monitored by alcohol production.

In the 3-L fermentation worts, FAN values in prepared worts reached 240 mg/L; in pilot brewery-scale trials, the wort FAN levels averaged 270 mg/L. Increasing the FAN level above these levels did not increase the rate of fermentation or the yeast performance, except in the case of the pilot scale fermentations, where marginal enhancement was seen when yeast food was added (Fig. 4).

The worts produced in the pilot brewery for the 3-L and for the pilot brewery-scale trials were not representative of production worts in terms of FAN levels. Production worts possess average FAN levels near 160 mg/L. The reason for such high FAN levels in the pilot brewery was later found to be caused by temperature stratification in the mash mixer. This resulted in a lower conversion temperature with concomitant higher proteolytic activity.

No difficulties were noted during fermentation in pilot scale. Real degree of fermentation values were compared with the control values. The time required for complete fermentation was 15 days for the 24°P worts and 11 days for the lower gravities. The 12°P control required eight days to finish. Although extended time was required for complete attenuation, higher inoculation rates normally would have been used, the magnitude of which can be calculated (5). It is possible that the yeast strain used could, through multiple high-gravity repitching experiments, be acclimatized to the higher gravities and thus shorten the fermentation time. The extended fermentation time required at very high gravities would offset the capacity-saving advantages created by very high gravity brewing, although the increased flavor and physical stability would allow a concomitant shortening of the cold aging period. As noted in bench-scale work, a less flocculent yeast must be selected and used to achieve more rapid and consistent typical fermentations. This may result in alternate cropping methods and the use of a yeast centrifuge.

Several reports (2,4,5,8) have advocated that, for high gravity worts to ferment properly, the pitching rate must be increased. Casey and Ingledew (5) recommended yeast levels of 1–2 × 10^6 cfu/ml per °P. In our work, normal lager fermentation temperatures of 14°C were maintained to ensure that product flavor was not altered, and the pitching rate was set at 12.5 × 10^6 viable cells per milliliter at all gravities to remove one variable from the tests conducted. Moreover, experiments at the 3-L scale had not conclusively proven that increasing the yeast concentration resulted in a better or faster fermentation. Regardless of the pitching rate, approximately the same amount of yeast is recovered at the end of fermentation. Differences expected relate to the rate of fermentation catalyzed by the higher cell concentration and the ability of the increased yeast concentration to efficiently use dissolved oxygen form the wort (6). A given wort will only support the growth of a particular number of new yeast. Higher pitching volumes, coupled with lower yeast recovery, would result in shortages of pitching yeast.

Some researchers (13,21) have indicated that yeast crop, flocculation characteristics, and yeast viability would be adversely affected by increased wort gravities. In this work, it was shown

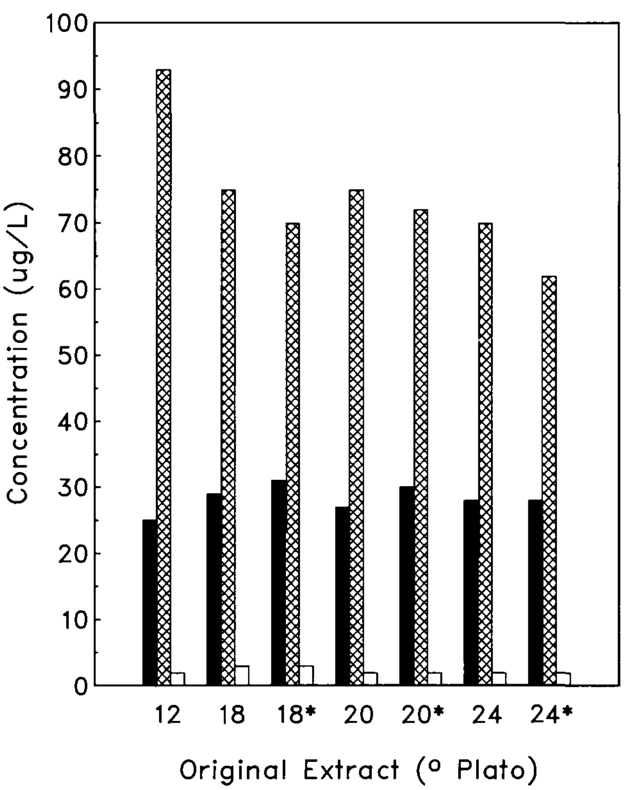

Fig. 7. Concentration of ethyl acetate, fusel alcohols, and isoamyl acetate after dilution to 5% (v/v) alcohol. Asterisk indicates added yeast food. Solid bar = ethyl acetate; patterned bar = fusel alcohols; clear bar = isoamyl acetate.

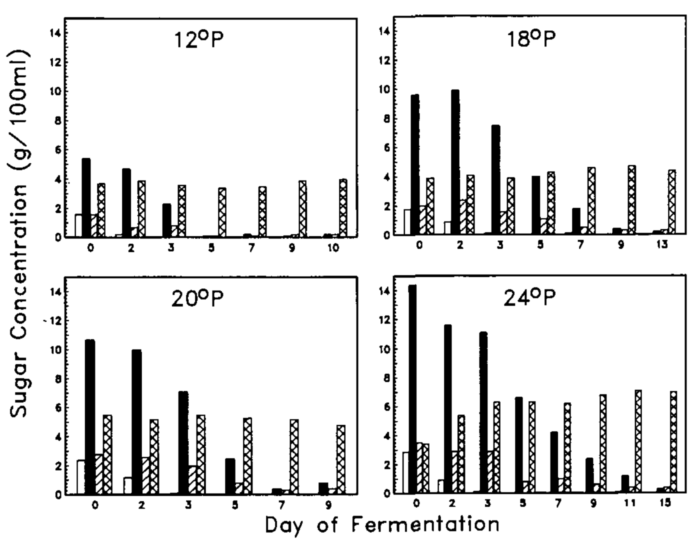

Fig. 8. Carbohydrate profiles during fermentation of the very high gravity (VHG) pilot plant experimentals without added yeast food. Clear bar = degree of polymerization (DP) 1; solid bar = DP 2; bar with diagonal lines = DP 3; bar with crossed lines = DP 4+.

that as the original gravity increased, the flocculation capability of the yeast appeared to decrease. This resulted in higher levels of yeast in suspension at the end of fermentation. This phenomenon, previously noted by Pfisterer et al (21), is thought to be caused by the combination of high osmotic pressure and ethanol concentration. This also may indicate the requirement of a centrifuge for yeast removal in VHG brewing.

Analytically, the VHG beers produced in the pilot brewery trials were similar to the control beers. The increased dilution ratio (50% for 24° P worts), necessary for producing a 5% (v/v)

TABLE V
Analytical Results from Undiluted Beers

	Original Wort Gravity						
Analysis	**12°P Control**	**18°P**	**18°P + Yeast Food**	**20°P**	**20°P + Yeast Food**	**24°P**	**24°P + Yeast Food**
Apparent extract (° P)	2.0	2.8	2.8	2.8	2.85	4.2	4.15
Real extract (° P)	3.85	5.74	5.74	6.15	6.2	7.56	7.54
Alcohol (%, v/v)	5.0	8.3	8.32	9.5	9.42	11.2	11.1
Color (SRM)[a]	2.34	2.25	2.21	2.09	2.19	2.01	2.15
pH	4.64	4.58	4.59	4.50	4.53	4.41	4.40
SO_2 (mg/L)	26	17	33	27	29	13	23
Vicinal diketones (μg/L)	10	16	16	3	13	2	3

[a] Standard Reference Method (1).

TABLE VI
Analytical Results for Very High Gravity Beers Without Yeast Food

	Original Wort Gravity			
Analysis	**12°P Control**	**18°P**	**20°P**	**24°P**
pH	4.64	4.9	4.8	4.8
Color (SRM)[a]	2.34	1.92	1.64	1.56
Apparent extract (° P)	1.60	1.35	1.25	1.56
Real extract (° P)	3.42	3.17	3.09	3.37
Calculated original extract (° P)	10.84	10.63	10.67	10.71
Alcohol (%, v/v)	4.91	4.90	4.97	4.86
Residual fermentable extract (%)	0	0.02	0.02	0
SO_2 (mg/L)	26	10.0	14.5	6
Vicinal diketones (μg/L)	10	10	0	0
Formazin turbidity units (FTU)	35	30	15	14
Sigma foam units	108	108	109	115
Five-Day forced FTU	75/76	35/35	20/19	14/14
Comments	Estery Grainy/Harsh Winey Hoppy	Estery Hoppy Smooth Light Winey	Estery Hoppy White wine Sweet Smooth	Estery Hoppy Winey Sweet Light

[a] Standard Reference Method (1).

TABLE VII
Analytical Results for Very High Gravity Beers With Yeast Food

	Original Wort Gravity			
Analysis	**12°P Control**	**18°P**	**20°P**	**24°P**
pH	4.64	4.88	4.9	4.91
Color (SRM)[a]	2.34	2.26	1.88	1.61
Apparent extract (° P)	1.60	1.29	1.12	1.46
Real extract (° P)	3.42	3.12	2.99	3.39
Calculated original extract (° P)	10.84	10.61	10.66	10.67
Alcohol (%, v/v)	4.91	4.92	5.03	4.79
Residual fermentable extract (%)	0	0	0.03	0
SO_2 (mg/L)	26	20	15	10
Vicinal diketones (μg/L)	10	10	10	0
Formazin turbidity units (FTU)	35	25	23	13
Sigma foam units	108	124	110	106
Five-Day forced FTU	75/76	29/30	27/27	12/12
Comments	Estery Grainy/Harsh Winey Hoppy	Estery Hoppy Winey Grainy	Estery Winey Harsh Hoppy Slight oxidation	Winey Alcoholic Estery Hoppy

[a] Standard Reference Method (1).

ethanol beer, resulted in reduced color, caloric content, and final SO_2 values. When yeast food was added, the final SO_2 values increased. Increased amounts of the amino acid methionine in yeast food-adjusted worts may have resulted in increased production of SO_2 by the yeast.

Beer pH was high for all brews, including the control. Elevated beer pH is reported to increase flavor stability (26–28). Increased dilution rates with production dilution water (intrinsic alkalinity of 85 mg of $CaCO_3$ per liter), and the exclusion of kettle acid during boiling contributed to the elevated pH of the final beers. Increasing physical stability was noted in the beers as the original gravity was increased (indicated by the decreased five-day formazin turbidity unit values). This phenomenon has been reported previously (28). Therefore, this is an indication that a better quality product can be produced at the higher gravities.

The volatile ester levels in the beers did not increase significantly as the original wort gravity increased. White and Portno (27) reported on the formation of extreme amounts of acetate esters in high gravity ale worts. It is believed that in our research, the use of a 14°C fermentation and the proper balancing of the initial wort oxygen levels and FAN levels with the added maltose syrup adjunct led to reduced ester formation (21,26). Upon dilution of the beers to 5% (v/v) ethanol, the ester levels were comparable to those of the control (Fig. 7). This confirms earlier results published by Casey et al (3).

Organoleptically, the beers produced were exceptional, receiving very high overall ratings. The beers produced at 18, 20, and 24° P were preferred to the 12° P controls. Additionally, the beers produced without yeast food supplementation were preferred to those where yeast food was added. This suggested that an increased proteolysis in mashing would be favored over the use of a high nitrogen yeast food.

The beers produced at 20 and 24° P were different from current production beers. They exhibited a very low residual sweetness and were thought to be lighter, smoother and more winey-estery than current production lagers. These differences are not unexpected in view of the high adjunct ratios of 40 and 50%, respectively, in the 20 and 24° P brews.

The very high gravity beers also were tasted (before dilution) by formal taste panels. These products were found to be extremely clean. The 24° P beer was very malty, sweet, hoppy, and bitter. It was described as being similar to barley wine. Nevertheless, a product of high alcohol content that takes advantage of savings from VHG technology has been developed.

CONCLUSIONS

Commercial lager yeast was able to ferment worts of original gravities up to 24° P (50% syrup adjunct) without yeast food addition. The beers that were produced exhibited better flavor and physical stability than beers produced at lower gravities. Organoleptically, the beers produced at 20 and 24° P were different from current production lagers. Generally, they were rated as lighter, sweeter, and smoother. The total long-term savings resulting from brewing with VHG technology may be significant enough that breweries will have to commit themselves to assess the production and palatability of the products made and described in this work.

TABLE VIII
Flavor Ratings[a] and Statistical Rankings of Very High Gravity Beers

Original Wort Gravity	Overall Ratings	Order of Preference
20° P	6.0 a[b]	2
18° P	5.9 a	1
24° P + yeast food	5.9 a	4
24° P	5.8 a	3
18° P + yeast food	5.3 b	5
12° P control	4.9 b	7
20° P + yeast food	4.8 b	6

[a] Based on a scale of 0–8.
[b] Any two means not followed by a common letter are significantly different at the 95% confidence level.

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