Kirk-Othmer Encyclopedia of Chemical Technology.

SUGAR, BEET SUGAR

For the 1995 crop year, beet sugar accounted for about one-third of the world's sugar production, ie, 40×10^6 metric tons of the total of 119×10^6 t (1). The European Union (EU) supplied 40% of the subtotal, the United States 10%, and the Ukraine, Turkey, the Russian Federation, and Poland together accounted for a total of 25%. Beet sugar is also produced in China, Egypt, Morocco, Iraq, Iran, Finland, Argentina, Chile, Canada, and most of the former Soviet bloc countries. With the exceptions of the Ukraine and the EU, all of the beet sugar is consumed in the country of origin.

The growth of the beet sugar industry can be seen by comparison of the 1995 figures with this 1910 quote:

> "The past year began with hysterical clamor for a change in the protective tariff on sugar, and other troubles that threatened the life of the beet sugar industry and which created doubts as to its stability and future growth. During the first six months of last year there were no new beet sugar factories promoted and there was not much work done to develop new sugar territory" (2).

The technologies described in this article represent the best practices of U.S. agricultural and processing facilities. Compared with European production, U.S. output of sugar per hectare has lagged both in absolute terms and in rate of increase (Fig. 1); both trends are expected to continue, and both represent sustained rapid progress derived from technical advances (3). The main factor tending to diverge European and U.S. trends is the increasing percentage of U.S. sugar beet crops produced on land that is not irrigated, leading to lower yields more than balanced by lower production costs. Two other factors, high energy costs and high profit margins protected by a series of quotas and tariffs, have assured a constant flow of capital to EU factories. Thus, most of the advances in processing technology and often the manufactured equipment originates in Europe.

For the 1994 crops, 33 beet sugar factories in the United States processed 28.8×10^6 t of beets from 586,000 ha into 4.23×10^6 t (93×10^6 Cwt) of sugar; 56% of the domestic production and 47% of the U.S. market. Cwt or hundred-weight of sugar is 100 lbs and is the common unit of commerce in the United States. This is a record level of production, an increase of 12% from the 1990 and 1991 crops. The average factory has a daily processing capacity of 4885 t compared to <3700 t in 1982. Since 1994, three factories in California have been closed and the construction of one new factory has been announced for central Washington State. European factories process 10,000–15,000 t/d.

Processing strategies vary considerably. The simplest scheme is to process the daily delivery of sugar beets directly to sugar, pulp, and molasses, storing beets only long enough to maintain a 24-hour operation. Such facilities produce sugar and by-products only when the crop is being harvested and must maintain an inventory of semifinished product(s) for year-round deliveries to customers. Elaborations of this simple scheme are aimed at extending the number of days of operation, increasing the annual production, and thus minimizing the potentially long periods of idle equipment. (*1*) Within a few hundred kilometers, locate microclimates and develop areas for growing beets which extend the number of harvest days. This is most practical in California, having a variety of microclimates. (*2*) Store beets during the relatively short harvest period to extend the number of processing days past the harvest period. Under favorable storage conditions of the cooler northern

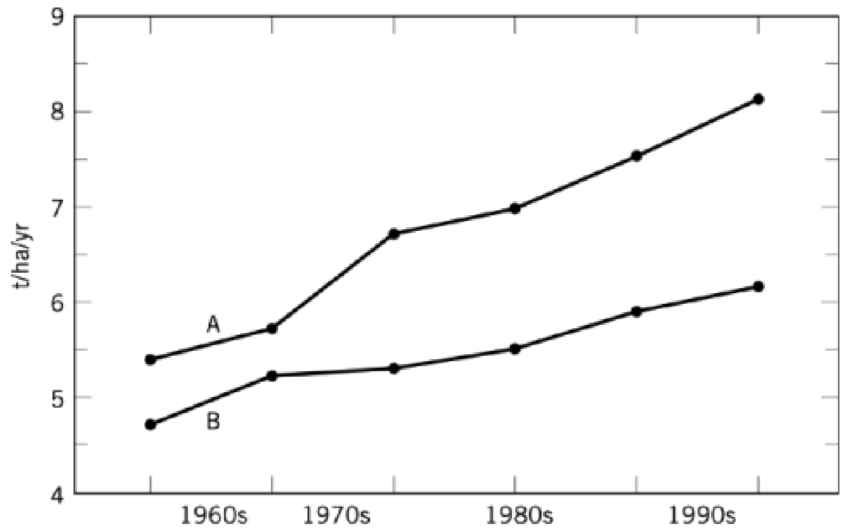

Fig. 1. Recovered beet sugar per hectare, 1960s–1990s, where A represents the European Union and B, the United States.

climates, exposed piles of beets can add another 120–150 days to the processing season. If several days of intensely cold weather occur early enough in the Fall, forced ventilation of beet piles can be used to freeze the entire pile and may add an additional five or six weeks to the schedule. Finally, the construction of covered sheds with internally circulating air systems affords preservation of frozen piles of beets well into the Spring months. (*3*) Increase the daily beet processing capacity and store the in-process purified, concentrated (thick) juice in large storage tanks. The final processing steps of crystallization take place during a "juice campaign" when beets are no longer available. (*4*) Install one of several similar systems to chromatographically separate sucrose from molasses, and use this thick juice to add production days to the calendar. Commonly, several factories ship molasses to such a facility which may operate 300+ days each year. This is also an effective tactic to increase the daily production rate of sugar even if the number of days during which beets are sliced remains the same.

1. Agricultural Practices

The sugar beet, *Beta vulgaris*, is a hearty biennial which produces crops of commercial impact in a wide range of climates, from the irrigated deserts of California's Imperial Valley, the high plains of Texas, the eastern slopes of the Rocky Mountains, the Great Lakes region, and Idaho's Snake River Valley, to the rich soils of the Red River Valley of North Dakota, Minnesota, and Manitoba, Canada, where a growing season as short as 100 days supports profitable crop yields. The crop is harvested at or near the time of the first hard frost (28°C) which terminates the photosynthetic production of sucrose and may threaten crop loss by freezing it in the ground. Whereas the Eastern and Idaho crops have to work around the cold winters, the nemesis of the Imperial Valley crop is the summer heat; the crops are planted in September and harvested from April through July. In northern California, the crop may be allowed to winter over for a Spring harvest, which must be completed before warm days trigger the seed production process that consumes much of the stored sucrose.

Besides traditional farmers' luck, a successful crop depends on seed quality and varietal characteristics, weed and pest control, timely irrigations or timely rains (not all beet crops are grown on irrigated land), disease control, crop rotations of at least three years, and a nitrogen management program designed to limit the amount of leaf growth to the minimum necessary to cover the rows and take full advantage of available sunlight. Most states that benefit from a healthy beet sugar growing–production system support the agricultural aspects through their University Extensions services, often in concert with USDA resources.

For a typical crop planted in the Spring and harvested in the Fall the following hold: for each hectare of land, 0.5 to 1 kg of seed (100,000 seeds/kg) are planted at 10 cm spacing in rows 55 cm apart that have been pre-fertilized. Nitrogen is by far the most important component of this fertilization treatment: too little, and the crop cannot thrive; too much, and the result is lush large crops with modest sugar content. The labor-intensive hoeing of beets has been displaced by planting to a stand of 65,000 to 85,000 plants per hectare. Mechanical thinning of beets is relatively rare.

The crop may be treated with pesticide 2 to 15 times, depending on insect and disease pressures in the area. Weed control is maintained by a combination of cultivation and pre-plant and post-emergence herbicides, and is not necessary after rows have been completely covered with a leaf canopy. All chemicals must be approved specifically for use on sugar beets by government regulatory agencies; the approved list gets shorter each year. The last irrigation usually occurs about six weeks prior to harvest, when the 1–2 kg roots are lifted with mechanical harvesters which defoliate the tops and leave them in the field.

2. Beet Receiving, Storage, and Handling Before Processing

Beets are loaded into side-dump or end-dump trucks in the field and taken to a receiving station, ideally located within 25 km but sometimes as remotely as several hundred km from the field. The receiving station may be the factory itself, an outside staging or piling ground which reloads the beets at a later date, or a rail car-loading facility which reloads the beets into open hopper cars for transport to the factory. At the receiving station the beets are unloaded from the truck and passed over a series of rotating grab-rolls arranged to allow trash, dirt, and small pieces of beets to fall out of the main stream. This first separation is especially important if the beets are destined for storage of more than a day or two.

Prolonged storage of sugar beets extends the factory processing campaign well past the harvest period sometimes by as much as seven months. During this storage period natural respiratory processes consume some of the sugar content of the root, reducing its commercial value. This loss of sugar can be further aggravated by yeast and mold infections beginning on bruised surfaces of beets and thriving when much dirt and trash are included in the storage piles. Because both processes are exothermic and accelerated by increased temperatures, poor storage conditions and practices can result in worthless piles of decaying material.

Commercial strategies for maintaining effective storage are (*1*) careful monitoring for unremoved leaves, trash, dirt, and early signs of rot or frost damage as the crop is received; (*2*) initially piling roots with temperatures between 0 and 5°C (never $>10^\circ\mathrm{C}$); (*3*) building large piles (Fig. 2) to stabilize temperatures and minimize surface area exposed to the elements (the largest piles are 70 m wide, 150 m long, and as high as 9 m; heights >7 m risk retarding natural ventilation which dissipates the heat of respiration); (*4*) carefully monitoring the condition of the piles to detect hot spots that can be processed immediately or discarded; (*5*) protecting the piles by covering with plastic sheets or straw; (*6*) mechanical ventilation through half- or full-round culverts placed under the beets as they are piled or in large sheds (60 m wide, 150 m long, and 10 m high at the sides) with an elaborate underground ventilation air recirculation–venting system; (*7*) using mechanical ventilation to deep-freeze the beets and stop respiration altogether (freezing usually requires four or five days of uninterrupted ambient temperatures $<15^\circ\mathrm{C}$). Once freezing begins, rewarming or thawing leads to spoilage.

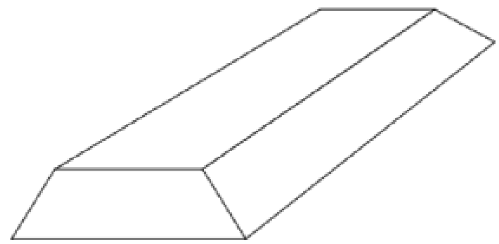

Fig. 2. Typical shape of a pile of stored sugar beets.

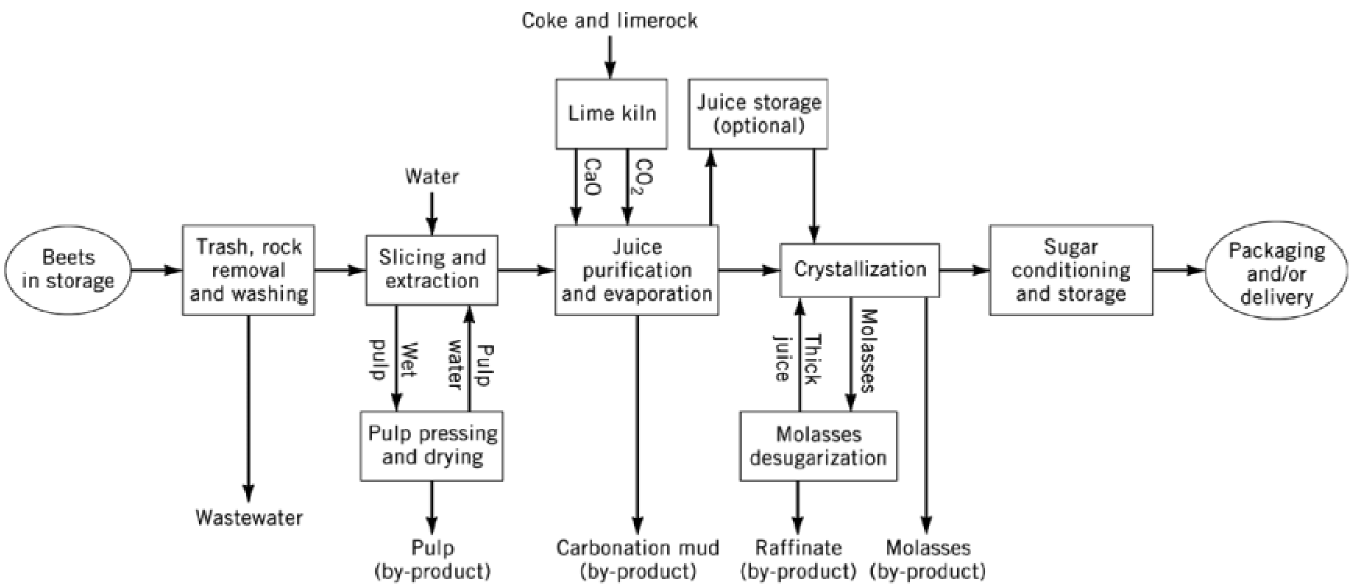

Fig. 3. Basic schematic of a beet sugar factory.

3. Processing of Beets to Sugar

A factory capable of processing 4500 t/d (capacities range from <3000 t/d to 12, 000 t/d) requires about 200 truckloads per day, moving to the factory, to feed the around-the-clock operation. Planning and logistics of beet receiving and transportation is an important element of smooth factory operation.

Whether beets are processed on the day of harvest or several months afterward, they arrive at the factory and are dropped into a cement trough of moving water which flumes them past a series of weed rakes and trash collectors. The neutral buoyancy of beets facilitates removal of stones and dirt. Spent flume water passes through a mud-removing clarifier 8–16 m in diameter and is reused, sometimes through a series of recirculating ponds. This water always contains some sugar and is unsuitable for discharge because of its high BOD levels. Such material is usually placed in holding ponds to allow the BOD levels to drop to acceptable levels, often leading to objectionable odors, particularly near residential areas. Some factories use anaerobic digesters to treat these waters and to avoid censure (Fig. 3).

Beets are either elevated or pumped to an agitated beet washer, after which they are rinsed with clean water. This rinse water is fed back to the washer from which it overflows back to the flume system, providing constant blow down. The beets are fed from bins to slicing machines configured either as a horizontal rotating

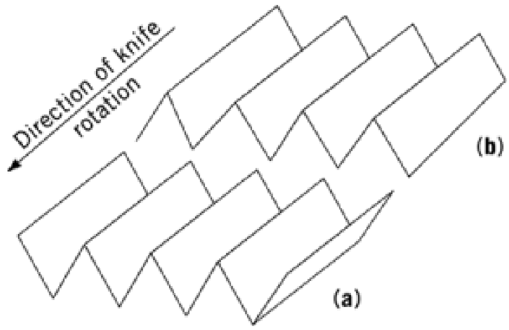

Fig. 4. Offset arrangement of slicer knives where (**a**) shows the first cutting edge, and (**b**), the second.

disk or a rotating drum where the beets and the blades are on the inside and the slices, called cossettes, fall to the outside. For both configurations, one knife makes a serrated cut across the face of the beet, followed by a second offset knife making a second serrated cut yielding elongated pieces with a diamond-shaped cross section 3–5 mm on a side and 4–10 cm in length. The knives can be adjusted in blocks to vary the thickness and length of the cossettes (Fig. 4). Long cossettes are always desirable and thickness is kept to the minimum which still allows the beet pieces to maintain integrity in the extraction step. Under the most unfavorable conditions where the beets have been frozen or decomposed and fall apart easily, the knives may be separated so much that slabs are produced.

4. Continuous Countercurrent Extraction of Sucrose

The extraction or diffusion process and the associated equipment usually define the overall beet processing capacity of a given factory. The diffuser, the centerpiece of this unit operation, may be capable of a throughput of more than 7000 t/d. The largest factories have multiple diffusers arranged to handle parallel flows of cossettes. For the many types of diffusers, the principle of operations is the same: cossettes are physically transported through the diffuser while water, which is introduced at the exit end and flows in the opposite direction as the cossettes, is constantly being mixed with the cossettes exit through screens from the end at which the cossettes are introduced. The amount of water introduced (draft) exceeds the weight of the cossettes by 5 to 20%; high draft leads to more efficient extraction of sucrose but at the costs of more energy spent on drying and evaporation and possibly higher extraction of impurities.

Extraction processes applied to sound, unfrozen beets are designed to allow the sucrose to diffuse from the beet cell wall mass and leave the intercellular material within the cells. Partial denaturing of the cell walls is accomplished by pre-scalding or heating cossettes after they leave the slicers, enough to allow free passage of the solution phase without rupturing the cell. Temperatures within the diffuser are maintained by using hot process water and indirect heating with low pressure steam. Maximum temperatures range from 50 to 70°C, depending on the integrity of the cossettes, the choice of diffuser design, and available heat-exchange capacity.

The three most common diffuser configurations are a vertical cylinder in which the semifluidized cossettes are scrolled upward (tower), a pair of upward-moving inclined twin-screw scrolls with cascading juices (slope), and a horizontal rotating drum equipped with offset compartments which allow the cossettes to fall forward as the drum turns (Raffinerie Tirlemontoise (RT) horizontal). Residence time within all of these diffusers is typically 45 to 60 minutes.

Spent cossettes (pulp) exit the diffuser with a moisture content of ca 92% and a sucrose content of ca 1%. To maximize the amount of sucrose returned to the process and minimize the amount of energy required to dry the pulp, this wet pulp is pressed in tapered twin-screw presses fitted with perforated side screens. On exiting the presses the moisture content of the pulp is ca 75% and the sucrose content ca 1%, which means that ca 2% of the sucrose that enters the factory with the cossettes leaves with the wet pulp (pulp loss). Water from the pressing step is passed through Dutch States Mines (DSM) screens and returned to the diffuser. The pressed pulp is normally mixed with molasses, dried to ca 10% moisture in rotating drum driers, stored, and sold as cattle feed, either as free shreds or pellets. Occasionally some of the pressed pulp is sold as-is to local feed operations. Processors in California use large cement strips, often disused airport runways, to solar dry wet pulp and save energy costs.

Improvements in pulp pressing technology have enabled manufacturers to reduce the moisture content of pressed pulp from 80% (moisture-to-solids ratio 4:1) to 75% (3:1 ratio), which has reduced the drying requirements by one-fourth. Beet pulp is much more difficult to press than most vegetable products, but there are indications that moisture in the mid-60% (ratios $<2:1$) range may be achievable with properly designed equipment.

The diffusion process has not been designed to ensure sterility, although temperatures above 65°C significantly retard microbial activity. Sulfur dioxide, thiocarbamates, glutaraldehyde, sodium bisulfite, and chlorine dioxide are all used, occasionally disregarding their redox incompatibilities, to knock down or control infections. The most common addition point is to the water from the pulp presses as it is returned to the diffuser. Surfactants are almost always used to control foaming in the diffusion process.

The raw juice exiting the diffuser is a murky dark gray solution occluded by colloidal materials from the ruptured beet tissue, small pieces of cossettes, and fine soil that escaped the fluming and washing processes. It is microbiologically and chemically unstable and unsuitable for concentration and crystallization. Common parlance assigns juice to more dilute process streams and syrup (or occasionally liquid) to steams with solids concentrations $>70\%$.

5. Juice Purification

Raw juice is heated, treated sequentially with lime (CaO) and carbon dioxide, and filtered. This accomplishes three objectives: (*1*) microbial activity is terminated; (*2*) the thin juice produced is clear and only lightly colored; and (*3*) the juice is chemically stabilized so that subsequent processing steps of evaporation and crystallization do not result in uncontrolled hydrolysis of sucrose, scaling of heating surfaces, or coprecipitation of material other than sucrose.

Active lime and CO_2 are produced as needed by calcining lime rock in kilns fired with gas or metallurgical coke. Typically the uniformly sized lime rock and coke, in a 12:1 ratio, are dumped in the top of a vertical kiln and withdrawn from the bottom. They travel through fire and cooling zones so that the rock reaches a maximum of ca 1000°C without overburning which leads to unreactive CaO. Carbon dioxide, both from the lime rock and the combustion process, is withdrawn from the top of the kiln, washed, and sent to the process, while the CaO is mixed with dilute in-process streams (sweet water of ca 4–8% solids content) to form a CaO–water slurry (milk of lime) of ca 30% solids content. This is metered to the various points in the process where needed. Overall consumption of lime rock ranges from 2 to 5% rock on beets by weight. Alternatives to the coke-fired vertical kiln are firing the kiln with oil or natural gas and the gas-fired horizontal rotary kilns used in the cement industry.

The equipment and complexity of the juice purification scheme depend on the nature and variability of the raw material and on the performance of the preceding washing, slicing, and diffusion steps. Some of the more elaborate systems have been designed to be reconfigured on the run as the nature of the beets changes during the campaign.

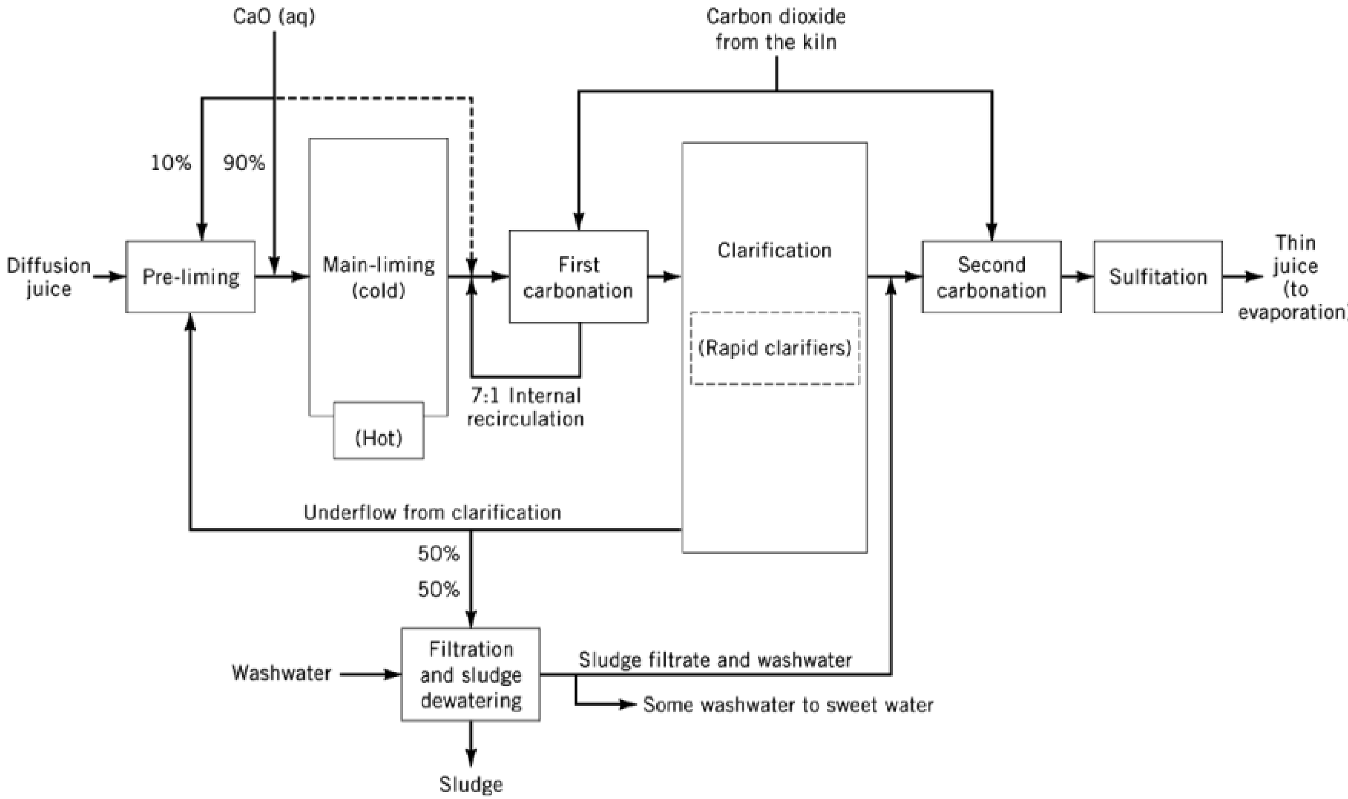

Fig. 5. Juice purification unit operation schematic where retention times are proportional to the size of the boxes and (–) are common optional processes.

5.1. Unit Operations

The chemistries elaborated by all of these systems are described by seven unit operations (Fig. 5). The first six, the use of lime and carbon dioxide as clarification agents, were laid out during the first half of the twentieth century and only the application technology has changed since, mainly from small batch processes designed to handle 1000 liters in a few hours to continuous systems capable of processing up to 10,000 L/min.

5.1.1. Pre-liming

Lime slurry, 0.25% lime on juice (0.250 g of CaO/100 g juice), is added to bring the pH of the mixture into the alkaline range. Insoluble calcium salts are precipitated as finely dispersed colloids. Calcium carbonate in the form of recycled first carbonation sludge is added to provide colloid absorption and stabilization. Temperature may be cool (50°C) or hot (80°C) depending on the temperature of the next step, or occasionally on the type of diffusion equipment. Retention time is 15 to 30 min.

5.1.2. Main Liming

A further 1.50% CaO on juice is added and the juice is brought to its maximum alkalinity and pH. Conditions may be cool (50°C for $\leq$60 min, followed by 5–10 min at 80°C) or hot (80°C for 10–15 min). The invert sugars (glucose and fructose) are converted to organic acids, which do not form insoluble calcium salts. If this reaction does not take place in the early stages of the process, before pH stabilization, it almost always occurs later and is characterized by dropping pH and rising colors throughout the evaporation crystallization steps.

5.1.3. First Carbonation

The process stream pOH is raised to 3.0 with carbon dioxide. Juice is recycled either internally or in a separate vessel to provide seed for calcium carbonate growth. Retention time is 15–20 min at 80–85°C. pOH of the juice purification process streams is more descriptive than pH for two reasons: first, all of the important solution chemistry depends on reactions of the hydroxyl ion rather than of the hydrogen ion; and second, the nature of the $CO^{2-}{}_3$–H_2O–Ca^{2+} equilibria results in a pOH which is independent of the temperature of the solution. All of the temperature effects on the dissociation constant of water are reflected by the pH.

5.1.4. Clarification

Clarification is also referred to as sludge separation. First carbonation effluent is passed through a continuous clarifier where the precipitated calcium carbonate is allowed to settle while the clear juice overflows to second carbonation. Clarifiers may be rapid (10–15 min with increased flocculant, 10 ppm vs 2–3 ppm) or slow (45–60 min). The sludge that is not recycled to the pre-limer is dewatered by vacuum filtration. The sludge by-product is stored in large piles and may be sold as a soil amendment; the filtrate is returned to the process. The Spreckels factory (Mendota, California) reburns this sludge in a rotary kiln to reconvert the calcium carbonate back to lime.

5.1.5. Second Carbonation

Calcium is reduced to the practical minimum by the addition of carbon dioxide at a pOH of 4.5 at a temperature of as near to 100°C as possible. This is the maximum temperature in the purification process and the retention time is only long enough to effect the pOH adjustment (5 min). The sludge from this unit operation is much less in amount than for first carbonation and is easily removed by in-line filters. The filtration is made even easier by the fact that the precipitate is almost pure calcium carbonate not fouled by the colloids found in first carbonation sludge.

5.1.6. Sulfitation

Sulfur dioxide is added to a level of about 150 ppm on juice to discourage further color-forming Malliard reactions by tying up the small amount of invert sugars as bisulfite addition compounds.

5.2. Juice Purification Chemistry

Lime in juice purification serves as a source of calcium, a source of alkalinity, and a source of calcium carbonate which serves as the clarification–filtration medium.

As a source of calcium, lime reacts with nonsucrose components to form a precipitate. Roughly one-third of these materials, by weight, form precipitates with calcium. Examples of such reactants are proteins, citrate, sulfate, saponins, phosphate, pectins, oxalate, and sulfite. The other two-thirds of the nonsucrose components remain in solution and salt-in sucrose reducing yields during subsequent crystallization steps. Diffusion juice components which do not precipitate with calcium include sodium, ammonia, nitrite, potassium, nitrate, betaine, magnesium, chloride, lactate, acetate, raffinose, glucose, glutamine, fructose, levans, and dextrans.

The stoichiometric ratio of lime to removable nonsucrose components is nearly five or six to one. This excess calcium is removed by the addition of carbon dioxide to form calcium carbonate, which is the primary clarification agent. Suspended or colloidal materials are adsorbed onto freshly precipitated calcium carbonate. These suspended or colloidal materials include not only those in the diffusion juice but also finely suspended precipitates of calcium salts. In sucrose solutions, $CaCO_3$ precipitate has a slight positive charge which is most effective at agglomerating negatively charged juice colloids. If the beets have been grown in clay-bearing soils, and washing does not adequately remove adhering soils, some of the clay may be present in juice as positively charged colloids. Unfortunately, these positively charged clay colloids have exactly the wrong chemistry for easy agglomeration and must be removed by the bulk filtration of the calcium carbonate.

High alkalinities of limed juice serve several functions. Foremost is to retard sucrose hydrolysis, one of the oldest reactions in the literature of chemical kinetics (6). Sucrose hydrolysis proceeds much more slowly at a moderately high pH than at an even slightly acidic pH.

Sucrose hydrolysis: reaction and kinetics

$$\text{sucrose} + \text{water} \xrightarrow[\text{salts}]{[\text{H}^+] \text{ or } [^-\text{OH}] \text{ heat}} \text{glucose} + \text{fructose}$$

$$\text{rate} = k(\text{sucrose})$$

$$k = k_{[\text{H}^+]}[\text{H}^+] + k_{[^-\text{OH}]}[\text{O}^-\text{H}]^{0.3} + k_{[\text{salt}]}[\text{salt}]$$

Not only is sucrose yield directly reduced as this reaction proceeds, but more nonsucrose components are formed. If 1% of the sucrose in a juice is hydrolyzed, it turns into $\sim$1% nonsucrose components and the resultant loss to extraction is 2.5% (1% directly + 1.5% reduced crystallization yield). Each metric ton of the newly formed nonsucrose material salts 1.5 t of sucrose into molasses. The reaction has commercial significance at levels of only a few hundred parts per million.

High alkalinity not only protects sucrose from acid hydrolysis, but also helps produce a stable thin juice by acting on specific nonsucroses. The invert sugars glucose and fructose are oxidized to organic anions; lactate is the most common. If this reaction does not occur early in the sugar production process, glucose and fructose participate in Malliard reactions with free amino groups on other nonsucrose components, followed by Amadori rearrangements (7), and eventually produce medium to high molecular weight colorants. Excessive amounts of these colorants in crystallizing syrups frustrate the production of white sugar and lead to rework.

Glutamine, the most abundant amino acid in sugar beets and raw juice, is converted to 2-pyrollidinone-5-carboxylic acid and ammonia. The reaction is promoted by heat and the ammonia is driven off by the high pH of the process streams. The odor of ammonia is often easily detectable in beet sugar factories. Healthy, mature beets generally contain manageable amounts of glutamine, for which all purification systems have been designed. Immature beets contain appreciably higher levels of glutamine which leave residual amounts in thin juice. During evaporation ammonia is driven off and pH drops, sometimes leading to slightly acidic syrups. The most common way to counter this pH drop is by the addition of soda ash to second carbonation. Unfortunately, this addition increases the nonsucrose level of the juice.

5.2.1. Nonsucrose Components from Storage or Damage of Beets

Some nonsucrose components are associated with the conditions under which the beets have been stored prior to processing, as respiration products or products of microbial attack. In either case they directly and indirectly reduce sucrose yield and may cause other processing problems. Glucose and fructose have already been discussed and can derive from either source.

Raffinose, a nonreducing galactose–glucose–fructose trisaccharide, is observed when the whole beet is subjected to long periods of cool weather, either in the ground or in storage. Betaine, zwitterionic trimethyl glycine that the sugar beet uses to regulate osmotic pressure within its cells, seems to increase just prior to freezing. Levans and dextrans, the slimy products of microbial attack, are removed in carbonation with great difficulty. Dextrans have been shown to ruin the chemistry calcium carbonate precipitation in carbonation, retarding coagulation with colloids (8). Usually, the amount of calcium carbonate (and hence the amount of lime) must be greatly increased to provide enough surface area to deal with these nonsucroses. Their presence is usually associated with degraded beets; although they can be a sign of factory process infections.

Nitrite is usually one indicator of the infection level in the diffuser. Exposure of nitrite to sulfur dioxide, either as a diffusion additive or later to thin juice, results in the production of potassium imidodisulfonate which precipitates when sugar is later crystallized, a cause of turbid or cloudy sugar.

5.3. Removal of Calcium Prior to Evaporation and Crystallization

The second carbonation step is designed to minimize the amount of calcium in thin juice by removing it as $CaCO_3$, the solubility of which is minimized by high temperature, high carbonate concentrations, and low nonsucrose concentrations. Counterbalancing these factors is the high solubility of calcium bicarbonate, which predominates as the pH drops below 8.4. The addition of CO_2 provides carbonate ion, but also lowers the pH. Upstream infection problems produce acids leading to lower juice pH. After prolonged heating the bicarbonate eventually expels CO_2 and produces carbonate, leading to $CaCO_3$ scaling on evaporation and heating surfaces, a common consequence and a significant cost increase in processing degraded beets. The minimum calcium content may vary from 20 ppm to more than 350 ppm depending on the raw material. Juice softening with resins, commonplace in European factories, has been installed in about one-third of U.S. factories, justified not only by process advantages but also by the need for molasses having low calcium/magnesium levels for molasses desugarization operations.

6. Crystallization and Recovery of Sucrose

The three-boiling scheme, typical of U.S. beet sugar production, is shown in Figure 6. Incoming thick juice is combined with recycled lower grade sugars, filtered, and crystallized under vacuum to yield about half the sucrose separated from the mother liquor and washed in batch centrifugals. The process is repeated two more times using continuous centrifugals for the separation of syrups and crystals; only the first crop of crystals is used for finished product. The third crop is washed with a slightly higher purity syrup (affined) to reduce the load of nonsugars and color. Both the second and third crops are returned to the first stage. After the liquor has been concentrated to about 10% past supersaturation, crystal growth is initiated by fully seeding each pan with enough crystals, 1–5 μm in diameter, to account for the finished pan.

All of these processes are carried out under kinetically controlled conditions and vacuum pan operations may be followed by a crystallizer in which the massecuite (crystals/mother liquor) is allowed more time for crystal growth, sometimes for as long as 48 hours for the third stage. Crystal growth is enhanced by higher purities, lower viscosities, higher concentrations, agitation of the crystallizing mass, higher temperatures, and time. The first boiling typically takes $1\frac{1}{2}$ to 2 hours; the second, 4 hours; and the final boiling, 8 hours or longer plus at least 12 hours of crystallizer time. Surfactants designed to reduce viscosities are commonly added to each stage. The batches are referred to as strikes, a holdover from the practice of initiating crystallization by hitting the pan with a large hammer or iron bar. Some older equipment may show signs of this abuse.

Crystallization batches range from 30,000 to 60,000 liters for each pan. Continuous centrifugals are typically used for second, third, and affination steps; continuous vacuum pans are less common but are used in the U.S. for intermediate strikes. Most horizontal batch crystallizers have been replaced by continuous units, and all are designed for controlled cooling of the massecuite to maintain supersaturation.

Balancing these crystallization steps to maximize the yield and maintain high product quality is a significant operational challenge, especially when confronted with changing thick juice quality, ie, color, purity, and pH stability (Table 1). These values reveal the critical dependence of performance on the quality of the thick juice and, by inference, on the nature of the beets. Calculations have assumed the same yield for each of the boilings. The higher nonsucrose loading has reduced the final yield by 5% for the low purity thick juice. For the same 100 kg of sugar entering crystallization, each stage of the low purity scenario has to handle 40–50% more material because of increased concentrations of returned sugar from the second and third stages. Because the

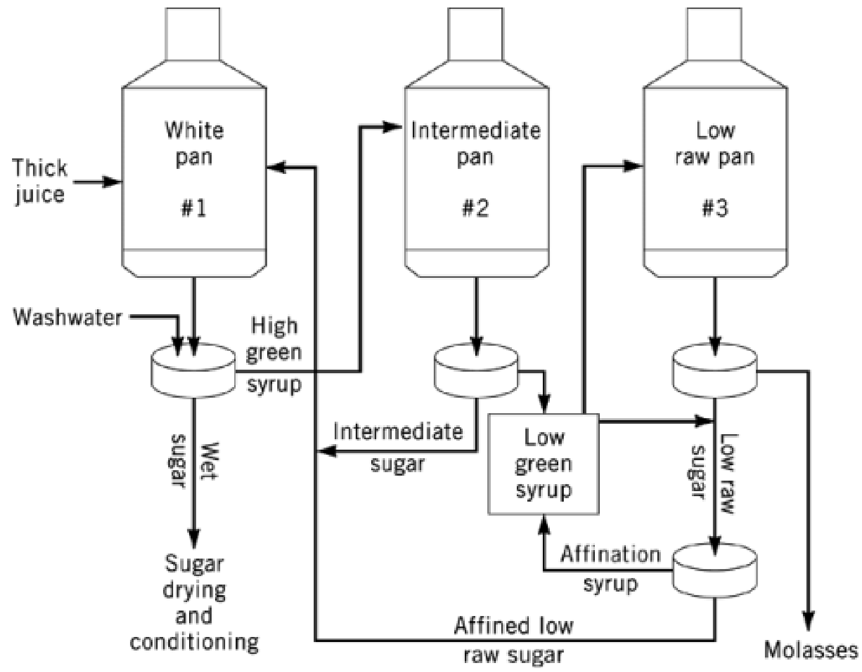

Fig. 6. The three-boiling beet sugar crystallization scheme.

Table 1. Material Balance and Purity Effects of Thick Juice Purity[a]

	Low purity juice		High purity juice	
Material	Sugar, kg	Purity, %	Sugar, kg	Purity, %
thick juice	100.0	88.0	100.0	92.0
white pan	208.2	93.5	143.8	93.9
intermediate pan	72.8	83.4	50.3	84.5
low pan	32.8	69.1	22.6	70.8
molasses	16.2	54.3	11.2	56.3
product	83.8		88.8	

[a] Purity = sugar content as percent of total dissolved solids content.

process is controlled by kinetics, either pan yields must be sacrificed or overall throughput must be reduced; either choice has costly results. Low purity juices tend to be less stable with respect to color, pH, and calcium precipitation, and the choice is always between bad and worse.

7. Conditioning and Storage of Sucrose

Washed, wet sugar contains about 1% moisture which must be reduced to about 0.03% without glazing over the crystals. This is accomplished in a rotating drum granulator–cooler in which warm air is passed over the crystals as they roll down the length of the drum. This is followed by cooler air to stabilize the crystals at $<35°C$ before conditioning. Best practices allow sugar to cure for 24 hours before long-term storage or shipping

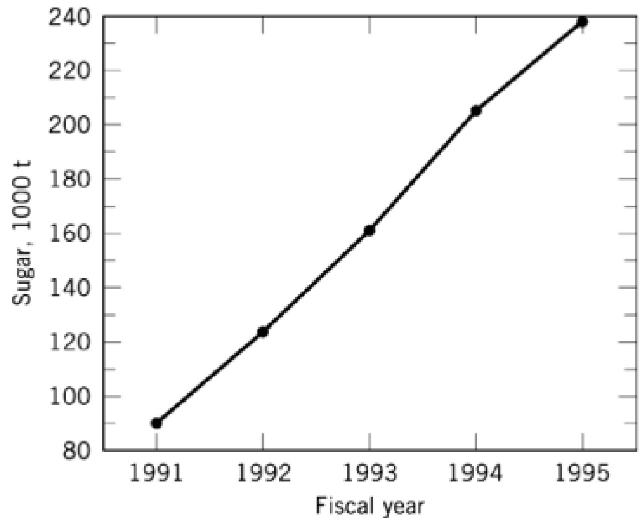

Fig. 7. U.S. production of beet sugar from molasses desugarization processes. Values for 1995 are estimated.

as bulk sugar in rail cars or trucks. The most common customer complaint for every beet sugar producer is hard and lumpy sugar caused chiefly by failure of these processes.

Because beets are processed for only a portion of the year, a factory may store as much as half of the production sugar in order to provide continuous distribution to customers. This is accomplished either in sets of tall, vertical cement silos, each capable of holding 6800 t, or single large-diameter Weibul-type curing silos of 23,000 t capacity. The cement silos are theoretically first-in first-out configuration in which the sugar is dropped in the top and withdrawn from the bottom; in practice, sugar tends to funnel through the center of the silo, resulting in a last-in first-out scheme. A Weibul silo has a central distribution column with a rotating arm which scatters the sugar allowing it to fall through dehumidified air in even layers about the bin. Withdrawing sugar is accomplished by using the same arm to rake sugar from the top toward the center where it falls to the bottom into an annular opening around the central column. This last-in first-out system provides the best conditioning for the product which must be stored the longest.

8. Molasses Desugarization

Chromatographic separation of diluted molasses streams into a high purity fraction suitable for concentration and crystallization and a second low purity by-product, which can be concentrated and sold as an animal feed product, has been employed in Finland since the 1970s and in the United States since the mid-1980s. Since the early 1990s, production of sugar from beet molasses has almost tripled, and the trend is expected to continue for the next two years to consume most of the domestic beet molasses (Fig. 7) (3, 9).

Strong cationic sulfonic acid resin beads of very uniform size (325 μm) are used as a stationary phase. Their active sites exist in a mixed sodium–potassium form depending on the makeup of the molasses being separated. Sugar has a slight affinity for these resins, betaine an even higher affinity, and most ions have little or no affinity, hence the term ion exclusion for this process. This places two fairly strict requirements on the feed molasses: the molasses must have low concentrations of calcium and magnesium ($<$500 ppm), which not only compete for the active sites but may precipitate within the resin bed, and the molasses constituents should be as uniform as possible so the nature of the resin is not constantly changing.

The separation uses either of two modes of operation: (*1*) a pulse method in which batches of feed are sequentially placed on the column and eluted with water, taking product and by-product fractions as desired, and (*2*) a simulated moving bed (SMB) configuration in which the feed is continually placed on the column at the point where its purity matches the separation. The pulse method provides more flexibility, less dilution, and better separations but suffers from a waiting time for the previous pulse to clear. The steady-state method has higher capacity and is easier to manage, but requires more valves on a series of sections in order to move the point of addition. The SMB separation is most effective when only two components are involved, ie, sucrose and salt or sucrose and betaine. Under normal operating conditions, 15 m of column length is required to economically separate molasses components on this 325-μm resin.

The product has purities typically in the 90–92% range and can be combined with thin juice, concentrated and crystallized, or concentrated and stored for later use. Crystallizing the desugarization thick juice apart from the normal beet campaign may be desired because the secondary molasses produced after the separation contains the nonsucrose components, which are the most difficult to separate from sucrose and perhaps should be set aside and sold instead of resubmitted to the columns.

The desugarization by-product is normally sold as a low value molasses. Pulse method systems also produce a relatively high value betaine-rich (at least 50% on solids) fraction. The concentrated betaine-rich by-product is used as a custom animal feed, whose European markets are well established and may provide a future opportunity in the U.S. feed industry. Beet sugar molasses contains from 3 to 6% betaine, by weight, about three-quarters of which may be recoverable as a potential by-product ($\sim 40 - 50\%$ purity).

9. Marketing and Economic Aspects

U.S. beet sugar producers share the domestic sucrose market with sugar produced from domestic sugar cane and imported raw sugar. The grower–processor beet contract is highly participatory. The processor determines the amount of acreage that a factory can support, based on historical yields and daily factory processing capacity. The grower and processor enter into a contract, before seeds are planted, in which the grower agrees to plant, nurture, harvest, and deliver the beets whereas the processor agrees to purchase the entire crop. Payment is based on the sugar content of the beets and the net selling (after selling expenses) price (NSP) that the sugar actually fetches in the market. The fluctuations in the market are shared between the sugar beet growers and the processors ($\sim 60:40$), and the variations in factory performance are borne by the processor.

The payment formula assumes that 85% of the sugar in the beet can be extracted and then $0.60 out of every sales dollar is returned to the grower. The details vary somewhat from region to region with allowances for such things as early deliveries, losses during beet storage, actual factory performance, transportation and retransportation costs, and beet quality parameters. The quality parameter premiums may include extra high sugar content and low levels of nonsucrose components which translate to higher in-factory sucrose yields. The average return to the grower is closer to $0.63 on the dollar.

Grower-owned cooperatives produce about 40% of the beet sugar in the United States. The revenues returned to these growers is also about $0.60 on the sales dollar, although the contractual arrangements and payment formulas are much different, ie, basically all residual revenues after operating and selling expenses have been paid are distributed among the growers according to the amount of sugar delivered to the factories.

The U.S. government supports the domestic beet sugar industry through low interest loans to processors, secured by finished sugar as collateral. The rate, $0.18/lb ($0.40/kg) raw value, is established by legislative mandate. The U.S. Department of Agriculture restricts the amount of raw sugar to keep the domestic prices high enough to avoid forfeiture of sugar. If the amount of imported sugar drops below a predetermined minimum quota level, the department has the authority to enforce market allocations and force beet sugar processors to withhold sugar from the market at their own expense. The quota distributes the U.S. sugar import needs among raw sugar exporting trading partners. The loans and market allocations were mandated by the 1990

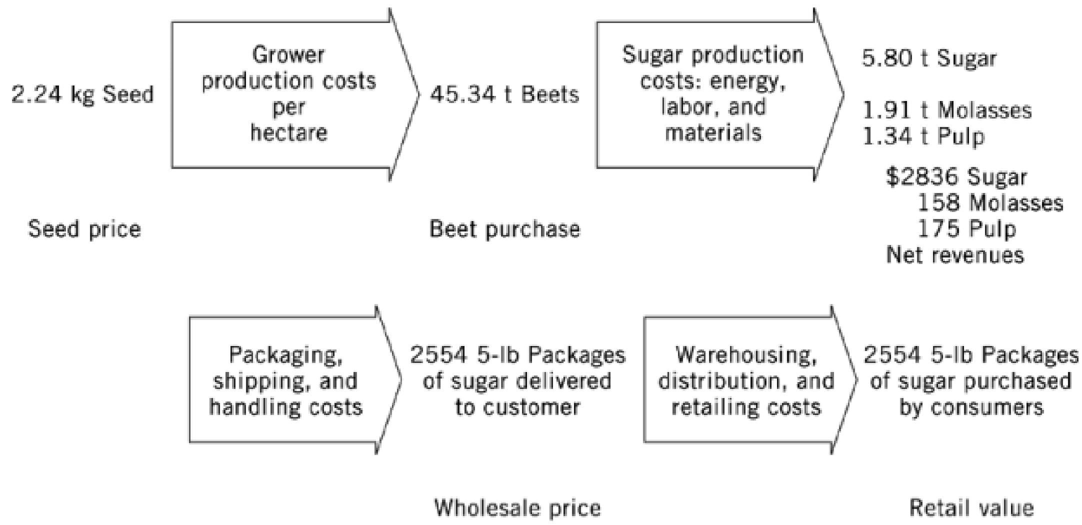

Fig. 8. Typical value chain for 1 ha U.S. beet sugar production. See text.

Farm Bill and have been reestablished in the 1995 version; the quota is part of the General Agreement on Tariffs and Trade and other trade agreements such as the Caribbean Basin Initiative and NAFTA.

9.1. Economics of Beet Sugar Production

Figure 8 presents the material and financial balances of production of 2500 consumer packages of sugar from 1 hectare. It starts with $99 worth of seed, which leads to $1771 worth of beet payments, from which $3169 worth of bulk sugar, pulp, and molasses is extracted, $3737 wholesale value after packaging, and finally $5187 on the grocers' shelves. About one-third of the increase in value from $99 to $5200 is realized by the grower, 40% by the processor, and, for this example, 28% by the wholesaling–retailing grocer.

With the current adequate supply of domestic sugar, the opportunity to increase net revenues by increasing prices is limited or diminishing. Growers and sugar producers must cooperate to maximize crop and factory yields while reducing their own costs. Margins are so slim that gains made by one group at the expense of the other surely weaken the relationship. Since 1970 this has led to the emergence of grower-owned cooperatives which combine the first three steps of the value chain (see Fig. 8), and which accounts for 40% of U.S. beet sugar production. This trend is expected to continue, not only by growers purchasing existing operating facilities but also through formal partnershipping, marketing agreements, and complex risk and profit sharing agreements between growers, producers, and perhaps even customers.

9.2. The Domestic Sugar Market

Figure 9 (10) traces the market trends for sugar in the United States by food use customer group. Overall the market is growing at a rate of 3–4% per year, with confectionery, baking and cereal, and ice cream and dairy products accounting for most of the growth. The sharp decline in the beverage segment between 1980 and 1985 represents the replacement of sucrose by high fructose corn sweeteners as the sweetener of choice. The increasing use of nonnutritive sweeteners seems to have created new markets rather than displacing existing sucrose markets.

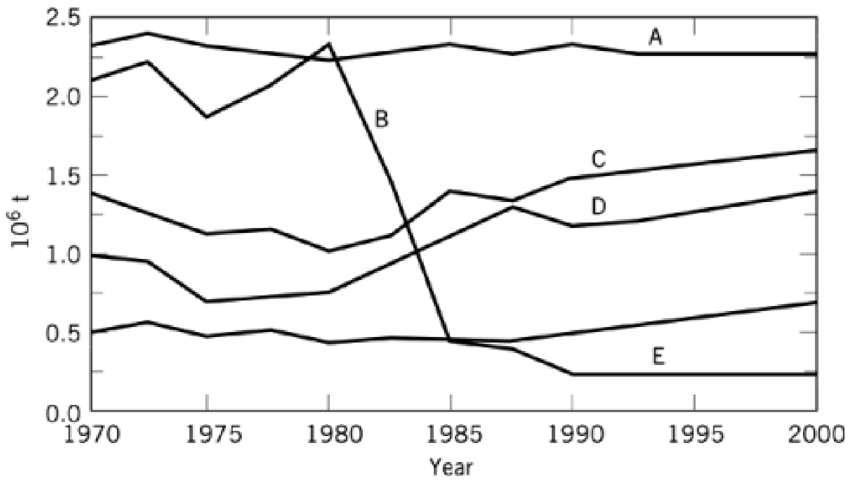

Fig. 9. U.S. sugar deliveries by customer group where A represents the consumer; B, beverages; C, baking and cereal; D, confectionery; and E, ice cream and dairy.

10. Product Quality and Requirements

The most common parameters used to measure product quality are moisture, color, granulation, sediment, and ash.

10.1. Moisture

Moisture is usually determined by a vacuum oven-dry method at 80°C. Moisture levels of more than 0.05% are likely to lead to caking or lumping problems which can make storage and transfer of bulk sugar difficult. The usual standard is 0.03%, which manufacturers can easily meet. Care must be taken to avoid temperature differentials in storage which cause moisture to migrate and establish pockets of unacceptably high moisture levels.

10.2. Color

Color is usually specified as white and measured as a solution color using the specific absorbance at 420 nm. If the measurement is made on a filtered (0.45 μ) solution, it is reported as International Commission for Uniform Methods of Sugar Analysis (ICUMSA) units. More commonly, a second transmittance reading is taken at 720 nm, a turbidity correction made, and the result reported in Reference Basis Units (RBUs). Turbidity can also be used as a quality parameter. Using either scale, sugar begins to be noticeably off-white at about 50 units. The upper limit is usually 35 units, which corresponds to a straw-colored solution at 50% solids. High color in sugar is a harbinger of other problems such as foaming, off-odors, cloudiness or floc, or generally poor performance in production which is why many customers who use sugar in highly colored or opaque products insist on low color sugar.

10.3. Granulation

Granulation is important to customers who do not want too much dust (fines), lumps, or grittiness, and/or who have a very specific need to mix the sugar with other dry ingredients or to turn it into a fondant. Customers in the latter categories are willing to pay a premium for specially screened sugar. Beet sugar is commonly produced with crystal sizes in the 0.400 mm range with a coefficient of variation of 25–30%. The size distribution is determined on a stack of three to eight sieves of decreasing sizes using U.S. Sieve values for reference.

10.4. Sediment

Sediment is most commonly used as an operational check of filter efficiency and leakage, although some customers, especially those who intend to melt the sugar into clear solutions, write sediment restrictions. The measurement is normally done by passing the 50% solution used for the color determination through a half black–half white filter pad and visually counting the white and black specks.

10.5. Ash

This can be determined by a gravimetric method using sulfuric acid to digest the sugar followed by burning in a muffle oven at 650°C. Measuring conductivity on the 50% solution and then referencing this value to the sulfated ash method is much more common. Typical values are 0.003–0.008%, with the upper limit on specifications usually written at 0.015%. Ash is a good indication of the general level of impurities in beet sugar and unacceptably high ash levels usually are accompanied by other problems. This is not an important parameter for cane sugar which can be quite acceptable with ash levels of more than 0.035% (see Sugar, cane sugar).

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MICHAEL CLEARY
Imperial Holly Corporation

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Sugar, Properties; Sugar, Analysis; Sweeteners; Syrups