Technology of the Rum Industry

Willem H. Kampen

Rum is defined in the labelling regulations of the U.S. Internal Revenue Service (27 CFR 5:21) as: "any alcoholic distillate from the fermented juice of sugar cane syrup, sugar cane molasses or other sugar cane by-products, distilled at less than 190° proof (whether or not such proof is further reduced prior to bottling to not less than 80° proof) in such a manner that the distillate possesses the taste, aroma and characteristics generally attributed to rum and includes mixtures solely of such distillates."

The regulations do not differentiate among the types of rum, although use of certain geographic designations of the label, *viz.*, Puerto Rico, Jamaica, Martinique and Surinam, is limited to rum produced in the particular area designated. Rums of different origins differ in character because of variations in a number of production factors, *i.e.*, the sugar cane variety, the molasses or sugar syrups involved, the type of rum yeasts used, the rate and length of fermentation, the proof at which the rum is distilled, the presence or lack of certain bacteria, added flavoring or coloring material, the length of aging in the barrel and the proof at which it is bottled.

Most rum consumed in the U.S.A. is light in flavor, which indicates that it is the product of relatively rapid fermentation, distilled in modern column stills at proofs between 180° and 190° and bottled at 80° proof. Light rum is used mostly in daiquiris and other cocktails, and in cooling drinks like rum and cola or rum collins. More full-bodied rums, including New England rum, as well as rum from Jamaica, Guyana, Trinidad and Barbados are used as ingredients in cocktails such as planter's punch, rum toddies, and zombies. Rum is mainly used for consumption, although some is denatured and used in toiletries and as a solvent for flavoring materials in the production of tobacco products.

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Table I

COMPOSITION OF A LIGHT AND A HEAVY-BODIED RUM.

(mg/100 ml absolute alcohol)

	Light	Heavy
Total ester-content as $CH_3CO_2C_2H_5$	32	412
Total acid-content as CH_3CO_2H	15	47
Total aldehyde-content as CH_3CHO	14	39
Total fusel-content as $C_5H_{11}OH$	39	217
	100	715

As a distilled alcoholic beverage, rum is heavily taxed, *i.e.*, US$10.50 per gallon of 100° proof (= proofgallon). For a fifth (gallon) of 80° proof this is US$1.68. Foreign imports have to pay an additional $0.28 duty per fifth of 80° proof. This output, of Puerto Rico, and to a lesser degree that of St. Croix, U.S. Virgin Islands, accounts for most of the U.S. beverage-rum consumption. Table I presents an example of the composition of a light rum and a heavy-bodied one.

Raw Materials and Their Properties. *Molasses.* Sugar cane juice is used, for instance, in the "rhumeries agricoles" in Martinique, where sugar cane syrups are used as well. However, the raw material containing the sugars is mainly cane sugar molasses, since the price per available unit of sugar is relatively low, compared with the other sugar cane derivatives. Furthermore, good-quality rums can be made from good-quality molasses. The quality of the molasses depends upon several factors, such as cane variety, growth conditions, process conditions in the sugar factory and storage conditions. Normal cane sugar molasses contains approximately 15 percent water, 33 percent sucrose, 18 percent invert sugar and 34 percent non-sugars, calculated on a weight basis. The non-sugars are a complex mixture of amino acids, salts of organic and inorganic acids, free organic acids,

vitamins, waxes, gums, pectins, hemicelluloses, etc.

Molasses used for the production of rum should, in general, have the following properties: high in fermentable sugars; low in ash, because this acts as an inhibitor for the growth of yeast cells and also yields scaling of heat exchangers and distillation columns; low in gums, since this also acts as a growth inhibitor for yeast cells; high in assimilable inorganic N and in P_2O_5, since this is required for yeast growth; a ratio of total fermentable sugars over ash of 6.5; a pH value of 5.5 to 6.0 in a 1:1 dilution with neutral distilled water, since lower pH values may indicate microbial infections and higher pH values may indicate the presence of free bases, which, in both cases, may yield contaminated final products; and a steam distillation should yield a fresh, sweet-sour, fruity-smelling distillate. Table II shows an example of good-quality and bad-quality molasses, judged from a rum-production standpoint.

Table II

COMPOSITION OF A GOOD AND A BAD MOLASSES QUALITY FOR THE PRODUCTION OF RUM

	Good	Bad
Brix	85.9	79.6
Total fermentable sugars in glucose	55.8	47.6
Ash	6.2	12.3
Total N	1.2	0.5
Total P_2O_5	0.3	0.1
Gums	1.1	3.4
CaO	0.8	1.9
pH (1:1)	5.7	4.8
Number of bacteria/milliter..	10^3	10^4
Ratio total fermentable sugars/ash	9.0	3.9
Steam distillation	fruity	sour
Color (Scale 1-1000, 100 = very dark)	64	88

Water. In the fermentation process, the weight ratio of water over molasses is approximately three; hence, large quantities of water are required. This water must be soft, clean, clear and free of any contaminants. The total hardness should be less than 80 milligrams calcium oxide or 57.1 milligrams of magnesium per liter. Furthermore, this water should not exceed 80° F., should be low in chlorides, have a low buffer capacity and a pH value not too far from 7.0. Water is also needed for the generation of steam and the cutting of the rum to 80° proof. It may be necessary to use ion exchangers and activated carbon filters to improve the quality of the water. Large quantities of cooling water are also needed; however, this may be of a lower grade. In the Caribbean, seawater is frequently used as cooling water, although this requires special materials of construction.

Acid. Sulfuric acid is usually used to help maintain a low enough pH value during fermentation to retard the propagation of micro-organisms other than yeast cells. At the same time, it acts as a catalyst for several wanted reactions, *e.g.*, esterifications. The acid used must be of good quality and must not contain heavy metals, since these act as inhibitors to the yeast cells. Sulfuric acid plus a mixture of organic acids may be used instead of sulfuric acid. Rums high in esters can be obtained this way, although organic acids of the homologous series, acetic, propionic, butyric acid and higher, are expensive and do slow down the rate of fermentation considerably.

Rum Yeasts. The rum yeasts used belong to the strain *Saccharomyces cerevisiae*. Suitable rum yeasts may be found on sugar cane, from which it is isolated, and the yeast is selected by previous isolation of the micro-organism in pure culture. The pure-culture yeasts are typically kept on agar slants in the refrigerator, but may be kept almost indefinitely when freeze-dried. It is very important to obtain a proper yeast strain, since its kinetics determine, under given circumstances, the fermentation efficiency and time, rum quality, etc. A suitable rum yeast produces a fair yield of alcohol, based upon the total quantity of fermentable sugars present initially, does so in a reasonable fermentation time and yields a raw rum distillate with a well-balanced chemical composition and the characteristic rum properties.

The rum yeasts are unicellular, facultative anaerobic organisms. Under aerobic conditions, the cells mainly propagate, while ethyl alcohol is formed under anaerobic conditions. Pure-culture yeasts do produce higher yields than baker's yeast, since they have good diffusion into the substrate, resulting in a more rapid and complete fermentation. Suitable rum yeasts may yield fermented mashes with 12 percent, volume per volume, alcohol, while baker's yeast usually does not exceed nine percent, volume per volume.

Yeast Nutrients. Cane sugar molasses normally contains all the yeast nutrients, including vitamins and other growth factors, except nitrogen and phosphorus. The deficiency in nitrogen and phosphorus must be corrected by adding these elements to the mash in a suitable form. Used are: urea, ammonium sulfate, diammoniumphosphate and superphosphate.

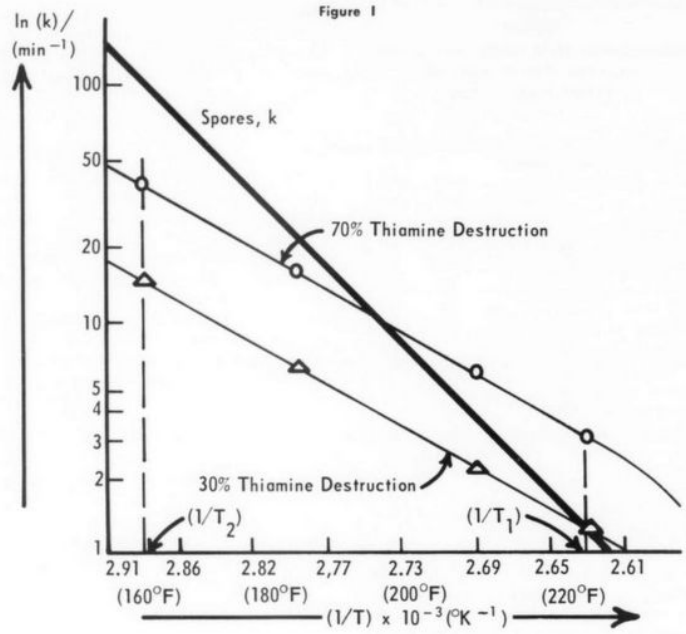
Air. In the aerobic process, the mash is strongly aerated for the propagation of the yeast cells. Since oxygen must cross gas-liquid interfaces, it may be the component limiting cell growth, if sufficient aeration is not present. The air has to be sterile and free of contaminants, such as oil. During compression, high temperatures are reached, assuring sterilized air, which makes cooling necessary afterward. The compression is isentropic and, with $k = c_p/c_v = 1.4$, 80° F. air being compressed fourfold will reach a temperature of approximately 343° F. This is easily cooled to 80° F. if cooling water of a lower temperature is available. To keep laboratory erlenmeyers "sterile," cotton plugs will do, and aerated tanks usually are equipped with fiberglass filters.

Dunder and Skimmings. Dunder is the bottom product of a distillation column; it is rich in both yeast nutrients and acids. Skimmings are the froth collected from the surface of the treated mixed-juice in the sugar factory; they contain ethereal oils. Both dunder and skimmings are quite often used in the production of more heavy-bodied rums, to which they impart a special character. Wild fermentations, still used in Martinique, Guadeloupe and Jamaica, quite often start off with a pH value of about 5.0, achieved by adding only dunder.

Bacteria. Suitable bacteria in pure culture may be used in the production of heavy-bodied rums. *Clostridium Saccharo Butyricum*, especially, may yield good results, since it produces from the proteins (amino acids) in the mash a mixture of acids. Ninety percent of the mixture is normal butyric acid, while the remainder includes: acetic acid, propionic acid, caproic acid and heptanic acid, which, finally, may give valuable higher esters. Mashes are usually not sterilized, but pasteurized, which forces the bacteria present to form spores, which may become active again during the fermentation process.

However, as a rule, the alcohol content has already risen too far for most bacteria to become active again. Lactobacilli are too stubborn to passivate for long; if present in considerable quantities, they may cause an off-taste

Figure 1



and off-odor in the distillate. They are able to produce 0.3 gram of lactic acid from every gram of invert sugar. Mash which is not sterilized or pasteurized should at least receive some antiseptic, such as sodium fluoride or ammonium bifluoride, to keep the degree of infection above 10. The degree of infection is the ratio of yeast cell concentration over bacteria concentration.

High-Temperature, Short-Time Pasteurization. Pasteurization of the mash will yield a more uniform final product. The goal is the thermal death of micro-organisms or loss of their viability, at least during the fermentation process. Continuous pasteurizers must be designed and operated so that the flow approaches piston-type flow, since only then does the mean velocity of the fluid equal the maximum velocity. In this case, the Peclet-Bodenstein number is infinite and the fraction of the fluid which will become overheated is essentially zero.

Plate or tube-type pasteurizers are mainly used. Diluted molasses solutions may be treated as Newtonian fluids, since they are relatively low in viscosity at elevated temperatures and easily achieve complete turbulent flow patterns. This improves the heat transfer and near optimal time-temperature curves can be achieved. On the basis of death-time curves for bacterial spores, it can be concluded that, in contrast to the normal pasteurizing required, *i.e.*, about 160° F., very short processing times are needed at about 220° F. These High-Temperature, Short-Time (H.T.S.T.) pasteurization methods are superior to all other methods used in the rum industry.

As a prototype for the evaluation of the retention of the nutrients, vitamin B_1, or thiamine, may be chosen. Thiamine is a water-soluable vitamin and is heat-labile at pH values above 3.5, while it has an activation energy of denaturation, which is representative of most common nutrients. The minimum thermal processing of the mash must sufficiently passivate the stubborn lactobacilli, since then it will have passivated all other spores long enough as well.

It is the difference in the magnitude of the activation energies for denaturation of spores and nutrients that makes continuous H.T.S.T. pasteurization so attractive. Other parameters involved are the fact that the lower the pH, the faster the required degree of pasteurization that is achieved, while the total number of organisms involved, as well as the type of organisms, have their influence on pasteurization time and temperature. The reaction rate constant k is calculated according to the Arrhenius equation:

$$\log k = (-\Delta E / 2.3.3\ RT) + C,$$

where, ΔE = activation energy, 50-100 kcal/mole for vegetative cells and spores (ΔE spores/ΔE nutrients > 1);
R = gas constant;
C = a constant; and
T = degrees Kelvin

Since, for a given reaction, E, R and C are constants, there is a linear relationship between (log k) and (1/2.303T) or (ln k) and (1/T). Figure I illustrates the reaction rate constants for spores and different concentrations of thiamine, showing that microbial destruction moves ahead of biochemical inactivation at increased temperatures with shorter processing times. During the mash pasteurization at 165° F. for 40 minutes, the required degree of pasteurization was achieved and 70 percent of the thiamine originally present was destroyed. The k value in this case follows simply from

$$^{0.7}dC/C = k^{40}\ dt \text{ and } -\ln 0.7 - (-\ln 1) = 40k,$$

thus $k = 8.92 \times 10^{-3}$ min.$^{-1}$

Since, for thiamine,

$$k = a.e.^{(-1.18 \times 10^4/T)} \text{ sec}^{-1},$$

the value for

$$a = (8.92 \times 10^{-3}/60)/(e^{-33.9}) = 7.87 \times 10^{10}$$

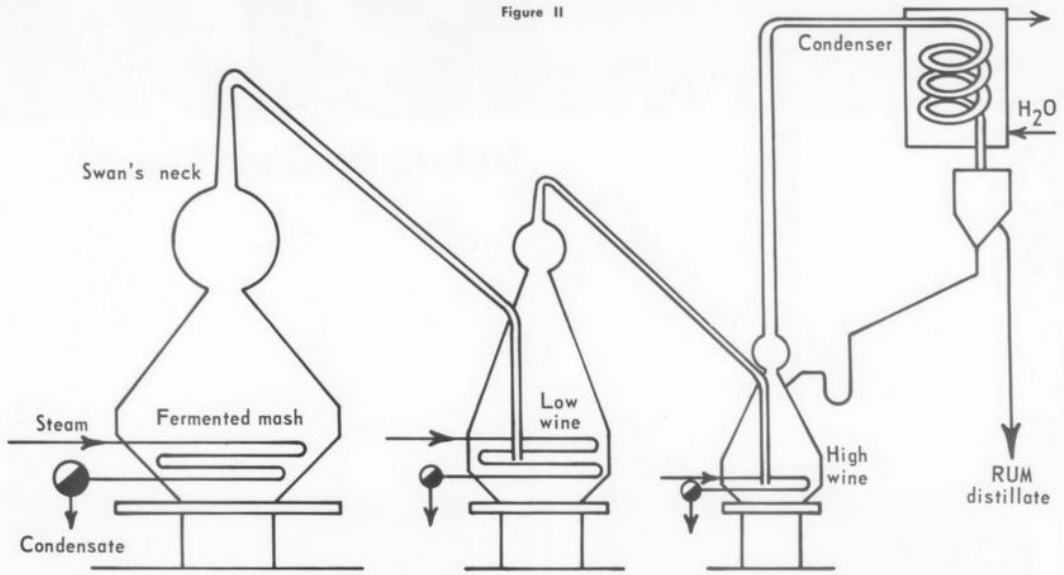
at the conditions of the mash (25° Brix and pH 4.9).

However, with the H.T.S.T. process, the required degree of sterility can be obtained in about 1.5 minutes at 225° F., while only 30 percent of the thiamine, and, consequently, other nutrients, are destroyed. The quality of the molasses may not be impaired and, therefore, the maximum pasteurization temperature is set by product browning reactions, *i.e.* Maillard and caramelization reactions. Practically optimal time-temperature curves will have to be determined for each fermentation system, such as Brix, pH and molasses composition.

The Fermentation Process. Several processes are in use, from completely wild fermentations to pure-culture batch fermentations. Continuous fermentation methods are not in use yet, although they certainly will be in the future. In the "rhumeries agricoles" (Martinique and Guadeloupe) two methods are in use:

In the first, sugar cane juice is diluted with water to a specific gravity of 1.04 to 1.05. The pH is adjusted to 5.8 with sulfuric acid. Some

Figure II



$(NH_4)_2SO_4$ may be added, as well as minor quantities of dunder. The wild fermentation then takes place in open tanks, which are quite often made of oak wood. To start the fermentation, a small portion of another fermenting batch may be added. No cooling is applied and temperatures may go as high as 110° F. The next step is a simple distillation, during which no fusel oil is removed, to about 160° proof, and then aging in oak wood barrels. The result is the "grappe blanche" rum with some 75 milligrams of esters per 100 millimeters of absolute alcohol. This type of rum is not very well appreciated outside of France.

In the second method, sugar cane juice is heated and allowed to settle. The clear juice is then decanted and concentrated in evaporators to a specific gravity of about 1.15. Large quantities of dunder are added, from 10 to 35 percent of the total volume, while water makes the balance to achieve a specific gravity of about 1.075. A wild fermentation and simple distillation, and aging in oak wood follow. These rums contain up to 160 milligrams of esters per 100 millimeters of absolute alcohol, and they possess a well-rounded-off character.

In the more modern pure-culture batch fermentation, the process is initiated in the laboratory by inoculating a special sterile broth with pure-culture rum yeasts. The flasks are placed in a shaker and, when a certain yeast cell concentration is reached, or usually after a fixed period, the contents of a flask are transferred to a solution of sterile molasses with added nutrients. After another two transfers, an 80-liter stainless steel projector filled with 50 liters of 18 to 24° Brix molasses and added nutrients at pH 4.8 is inoculated and strongly aerated. As an example, in the aerobic yeast propagating process, a 13,000-liter tank filled with 10,000 liters of 18 to 24° Brix molasses solution is strongly aerated until the desired yeast cell concentration is obtained. Due to the strong aeration, either no or almost no cooling has to be applied. The overall reaction in the aerobic fermentation is:

$$C_6H_{12}O_6 + 6CO_2 \longrightarrow 6CO_2 + 6H_2 + 625 \text{ cals.}$$

Most of the energy in this exothermic reaction is not liberated as heat, but used in the propagation process. The anaerobic or alcoholic fermentation which follows may take place in a stainless steel fermenter, such as a 110,000-liter unit filled with 100,000 liters of mash. The overall-reaction is:

$$C_6H_{12}O_6 \longrightarrow 2C_2H_5OH + 2CO_2 + 26 \text{ cals.}$$

Temperatures must be maintained around 30 to 33° C., and cooling is a must. In fermentations, the substrate gives rise to a mixture of end-products, some of which are more oxidized than the substrate and others more reduced. The techniques employed for the breakdown of carbohydrates vary widely in different microbial groups, as do the end-products formed. The rum yeasts and several bacteria use the Embden-Meyerhof method for the fermentative conversion of glucose to pyruvic acid. The yeast cells decarboxylate pyruvic acid to CO_2 and acetaldehyde, and the acetaldehyde is then reduced to ethyl alcohol. Several bacteria, some normally present in molasses, produce different end-products from pyruvic acid. Several aliphatic acids, as well as lactic acid, CO_2 and H_2, may be produced.

Pasteurization is mainly used to prevent this. With sufficient inorganic nitrogen present in the mash and with temperatures not exceeding 33° C., minimum quantities of fusel oil are formed. Fusel is the collective name for a number of primary aliphatic alcohols, all higher in molecular weight than ethyl alcohol, which formed out of amino acids and proteins by deamination. Isoamyl and active amyl alcohols are usually the chief constituents present, followed by n-propyl and isobutyl alcohol, as well as some isopropyl, n-butyl and, sometimes, n-amyl alcohol.

Similarly, succinic acid may be formed out of glutamic acid. The course of fusel oil formation is approximately concurrent with the ethyl alcohol formation, and the greater part of the fusel oil formation takes

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place after both rapid cell multiplication and rapid loss of amino acids have ceased. Fusel contents of approximately 0.4 percent in the mash begin to decrease the fermentation rate. During the fermentation process, the ratio of fermentable sugars over ash decreases continuously. As this happens, the yeast cell finds it increasingly difficult to obtain the sugars for its metabolism, while, at the same time, the increasing alcohol and mineral concentrations in the mash act as inhibitors toward the cell. For this reason, fermentation methods in which the fermentable sugar content is kept approximately constant through the logarithmic, or exponential, phase are superior to other methods.

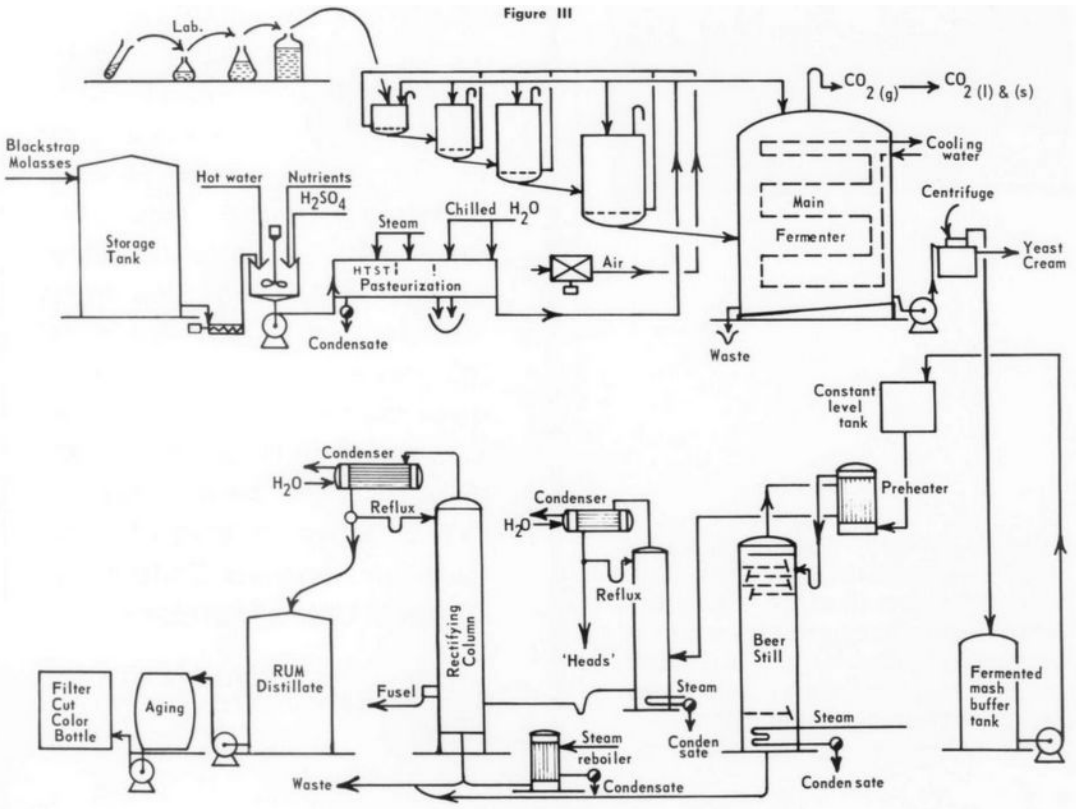
The alcoholic fermentation lasts around 45 hours, during which 25° proof may be obtained. Before the fermented mash is distilled, the yeast cells and most other solids present are separated out in a yeast centrifuge, since these predominantly organic compounds would otherwise decompose at the prevailing high temperatures in the beer still (220° F.) and foul the rum odor. Control in the fermentation process includes: pH, Brix, temperature, yeast cell concentration, degree of infection, alcohol content, dissolved oxygen content, etc.

The Distillation Process. Several methods of distillation are in use. In the production of heavy-bodied rums, simple stills like the pot still are in use (see Figure II). In the pot still process, which is a batch operation, the first distillate is the "low wine," which is distilled again and yields the "high" wine. Distillates of 130° to 160° proofs are obtained, but they contain, in addition to wanted impurities, or congeners, many unwanted impurities as well. Quite often, the "high wine" is distilled again, now in a rectifying column containing some eight to 12 trays, yielding a somewhat lighter rum. In the production of light rums, continuous distillation columns are used, usually with two or three in series.

The first column is the beer still, the purpose of which is to concentrate the feed to approximately 120° proof. The feed to the beer still is preheated to approximately 160° F. with the overhead products of this same column. The beer still feed is almost a saturated liquid and is fed in at or near the top, and the column is, consequently, a stripping one. It contains from 16 to 24 sieve trays in an all-copper or stainless-steel column. Sometimes, some copper strips are installed in the top part of a stainless steel beer still, in order to remove the sulphur components present. After leaving the preheater, the overhead product is fed as a saturated liquid to the second column, which is a rectifier, in the case of a two-column system, or an aldehyde column, in the case of a three-column system.

The aldehyde column contains from 16 to 24 bubble cap trays, and is usually fed in the middle. The overhead product goes to a total condenser and is fed back mainly as reflux. Some, called "heads," is withdrawn, since it is high in low-boiling constituents like aldehydes and ketones, and the bottom product is fed to a rectifier. The beer still and aldehyde column may both be heated directly with low-pressure steam; however, the rectifier

Figure III



must be heated indirectly, so no contaminants carried by the steam can end up in the distillate. Hence, rectifiers are supplied with reboilers.

Depending upon a two or three-column system and whether light or medium-bodied rum has to be produced, the rectifying column contains from 30 to 60 bubble cap trays and is usually fed at the tenth to twelfth tray from the bottom. The purpose of the rectifier is to concentrate the feed to the desired strength and remove the remaining unwanted impurities, which are mainly high boiling constituents (fusel). The fusel oil usually accumulates in the area from the tray above the feed tray to the intermediate trays of the column. The concentration reaches a maximum in the trays immediately above the feed tray, from which it is, then, withdrawn.

The fusel oil is completely soluble in ethyl alcohol; however, since it is less volatile, it is forced down the column by rectification. As the oils pass down to the bottom, they become immiscible in the higher water concentrations and "steam distillation" forces them to rise. Once equilibrium compositions have been reached, the fusel oil accumulation-band has a fixed plate number or, rather, fixed plate numbers. This band is displaced upward with lower reflux ratios and displaced downward with higher reflux ratios. The top product going to a total condenser is mainly withdrawn as rum; the remainder is reflux.

In the production of very light rums, the product is withdrawn a few trays from the top. The reflux ratios used are low, and range from 3:1 to 5:1 (reflux: rum distillate). Both rum distillate and "heads" go to daily production tanks via coolers, while the fusel oil goes to a washer and then to storage. Very light rum is distilled at 189.5° proof; light to medium-bodied rums at 188° to 180° proof. For uniformity in the rum quality, it is important to have adequate control instruments installed.

The complete distillation is carried out at atmospheric pressure. With a pressure drop of some 50 inches H_2O in the beer still, an increase to approximately 100 to 120 inches H_2O indicates it is cleaning time again. A good quality scale inhibitor is usually worth its price; in one particular case, cleaning once every two weeks could be changed to once every five weeks. Figure III schematically shows the process of producing light rums.

The Aging Process. There is a trend toward increased consumption of light alcoholic beverages, especially in the U.S.A. These beverages are low in fusel, and there is a positive correlation between the quantity of "fusel" consumed and a hangover. An excess of ethanol consumed will, however, still cause "headaches." The lighter the rum, the less impurities it contains, and less aging required. The ideal situation would, of course, be to produce a mature light rum straight out of the rectifying column, but this is impossible with present techniques.

The only reliable method of maturing a rum is aging it in oak wood barrels. It will be evident that a bad rum distillate will never become a mature rum through aging. A light-rum distillate with a well-balanced chemical composition may only need a few weeks of aging, while heavy-bodied rum distillates need up to several years. The barrels used are quite often second-hand whiskey barrels, which may be charred. During aging, several compounds, such as tannins, furfural, calcium salts, quercitine (a yellow dye-stuff), etc., are extracted. The quantity and type of extracted compounds depends upon, *e.g.*, time and temperature of aging, the proof of the rum, type and former usage of the barrel, and area of contact. Gaseous molecules may diffuse through the pores of the wood and, therefore, oxygen is available for several important, aging reactions. In most reactions, water is also formed, which accounts for the usual slight drop in alcoholic strength during aging.

The main reactions are esterifications, condensations and oxidations. Esterifications, which are molecular reactions, therefore require time. The ester present in the largest quantity is usually ethylacetate, although a combination of higher ester is more important for the final bouquet. In condensations, one mole of aldehyde combines with two moles of alcohol and forms an acetal. Oxidations can, for instance, provide acids for esterifications. Acetaldehyde may be oxidized to acetic acid, and ethanol may be oxidized to acetaldehyde, etc.

Fusel components may also break down into smaller components. The rate of aging is largely dependent upon the temperature and the area of contact, although there are also alcohol losses due mainly to evaporation. The rate of aging at 35° C. is approximately twice that at 25° C., and the alcohol losses per year also will jump from some five percent to 10 percent. When mature, the rum is filtered and diluted with pure, not too cold, water. The rum may be blended with another type of rum to obtain a special aroma and taste. The following steps are coloring with caramel, if required, and bottling.

Distillery By-Products. *Liquid Carbon Dioxide and Dry Ice.* In the anaerobic fermentation process, two moles of CO_2 are formed per mole of glucose utilized, while this figure is six in the aerobic fermentation process. On an overall basis, approximately 0.45 pound of CO_2 per pound of glucose utilized will be formed, which, after drying, purification and compression, may be liquefied and/or converted into dry ice.

Cattle Feed. The yeast and solids separated from the fermented mash may be mixed with additionally separated solids from the distillation bottom products, some molasses and bagacillo as well as other cheap cattle feed components available, to form pellets. *Cooking Fuel.* The "heads" may be sold as cooking fuel. *Fusel Components.* Fusel oil may be sold for the recovery of butanol as a solvent and amyl alcohol as a basis for amyl acetate. *Liqueurs.* Any modern rum distillery is able to produce most liqueurs.

Distillery Waste Disposal. Requirements for the discharge of wastes to surface waters will, of necessity, become increasingly critical. Using indirect heating in the distillation columns, condensate can be used as boiler feedwater, and the cooling water used in the plant may be used in a closed system, so either no discharge will occur or it may be used to dilute the waste. The production of cattle feed will ease the disposal problem. If a cattle feed-producing distillery is located near a municipal sewage-treatment plant, it may be allowed to discharge into that system. Otherwise, other methods have to be employed.

With low-cost land available and the plant located far from densely populated areas, lagooning may be the simplest treatment, for it can remove up to 95 percent of the biological oxygen demand (BOD) at a low cost. Trickling filters (moderate in cost) or activated sludge methods (high in cost) may be used, as well as anaerobic treatments (moderate to high in cost).

During anaerobic treatment, the organic compounds are first converted mainly into acids in a digester and these are converted by a mixture of methane bacteria into methane and carbon dioxide in a second digester. Sufficient methane is produced to keep the temperature of the sludge up to the optimum level of about 95° F. The anaerobic treatment method can handle heavy loads and yield an effluent with a low BOD, while it can be cheaper in both capitalization and operating costs than trickling filters and activated sludge methods.