fractions to cracked cycle stock derived from Mirando crude. The calculated conversions checked the observed data within an average deviation of about 15%.

It is hoped that utilization of the proposed $C_2$ and lighter severity index will enable greatly improved correlation between operating conditions in thermal conversion processes and yields and quality of products.

### NOMENCLATURE

$a$ = weight fraction of $C_3$ and heavier in reaction coil feed
$b$ = constant in Equation 2
$C$ = coil volume, cu. ft.
$D$ = coil inside diameter, ft.
$f$ = friction factor, dimensionless
$g$ = gravitational constant, ft./(sec.)$^2$
$G$ = mass velocity, lb./(sec.)(sq. ft.)
$k$ = compressibility factor, dimensionless
$K$ = reaction velocity constant for the feed to the reaction coil at given temperature, per sec.
$L$ = equivalent coil length, ft.
$m$ = constant in Equation 2
$M$ = molecular weight, lb./lb. mole
$P$ = pressure, lb./sq. in. absolute
$\Delta P$ = pressure drop, lb./sq. in.
$R$ = relative reaction rate, $K/K_s$
$t$ = time, seconds
$T$ = temperature, ° Rankine
$v$ = fluid specific volume, cu. ft./lb.
$\Delta v$ = $v_1 - v_0$
$V$ = flow rate through reaction coil, cu. ft./sec.
$W$ = flow rate through reaction coil, lb./sec.
$x$ = index components formed within reaction coil—for example, $C_2$ and lighter, weight fraction of reaction coil feed
$Z$ = fraction of total coil volume, considering total to be the portion above reference temperature—for example, above 800° F.
$\mu$ = viscosity, lb./(sec.)(ft.)
$\rho$ = fluid density, lb./cu. ft.

Subscripts
0 = point in coil where reference temperature—for example, 800° F., is reached
1 = coil outlet in Equations 1, 3, and 8, outlet of first section in Equation 4
2,3 = outlet of second and third coil sections, respectively, in Equation 4
$r$ = reduced temperature or pressure
$s$ = at reference temperature—for example, 800° F.
$T$ = total isothermal volume in Equation 1, total volume above reference temperature in Equations 3, 4, and 8

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# Madison Wood Sugar Process

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**A process, known as the Madison wood sugar process, has been developed for hydrolyzing mixtures of wood waste with 0.5 to 0.6% sulfuric acid at 150° to 180° C. by allowing the dilute acid to flow continuously through the charge of wood. Compared with the German Scholler process, hydrolysis was accomplished in less time because the sugars produced were removed more rapidly. Heating was at a lower rate, and more efficient use could be made of the heat given off by the liquors being removed from the hydrolyzer; steam requirements were therefore lower. Decomposition was less because the sugars were in contact with the acid for a shorter period of time and, consequently, yields of sugar and alcohol were higher. Fewer by-products inhibitory to fermentation were produced, so that fermentations were more rapid. Life of valves and other equipment was increased because they were set once for the run and not changed until the end of the run. The sugar produced in 2.8 hours from a ton of dry, bark-free, Douglas fir wood waste yielded 64.5 gallons of 95% alcohol as compared to 3.2 hours for 58 gallons by the rapid cycle method developed earlier, and 13 to 20 hours for 55 gallons by the Scholler process as carried out in Germany. These new findings indicate that the estimated capacity of the wood hydrolysis plant being built at Springfield, Oreg., may be increased from 4,100,000 to 5,950,000 gallons per year.**

PREVIOUSLY reported work (*3, 6, 13, 31*) on wood saccharification has shown that many of the steps in the process described by Scholler (*1, 2, 4, 5, 8–12, 14, 18, 20, 30*) are unnecessary and detrimental, and are responsible for making that process unsuitable for use in the United States. The batch addition of hydrolyzing acid, as used by Scholler for the treatment of the wood charge in the hydrolyzer, is responsible for the long periods required (16 to 20 hours), for the low concentrations of reducing sugars, and for the excessive consumption of chemicals. The steaming and rest periods between batches of acid promote the decomposition of sugar (*15*), cause unnecessary manipulation of controls, and contribute to a short life for valves and other essential parts of the plant. This report describes a new short process which includes: (*a*) a procedure for charging the digester, (*b*) a method of automatically controlled continuous addition of the acid at the top of the digester, (*c*) controlled removal of sugar solution from the bottom, (*d*) controlled hydrolysis to avoid decomposition and lignin plugs, (*e*) flashing the solution to a definite pressure so that methanol and furfural produced in the process may be recovered and excess steam may be used for heating of water, (*f*) neutralizing automatically under pressure, (*g*) filtering under pressure to remove calcium sulfate, (*h*) flash cooling of the sugar solution, and (*i*) filtering again to remove the organic precipitate that separates on cooling.

## PILOT PLANT EQUIPMENT

The equipment (Figure 1) consists of a hog chipper for converting wood waste to the proper size for hydrolysis; elevating equipment; a triplex pump for water (capacity variable from 2 to 10 gallons per minute); an acid pump (capacity variable from 0.2 to 4 gallons per hour); a switch, on the valve that opens the line

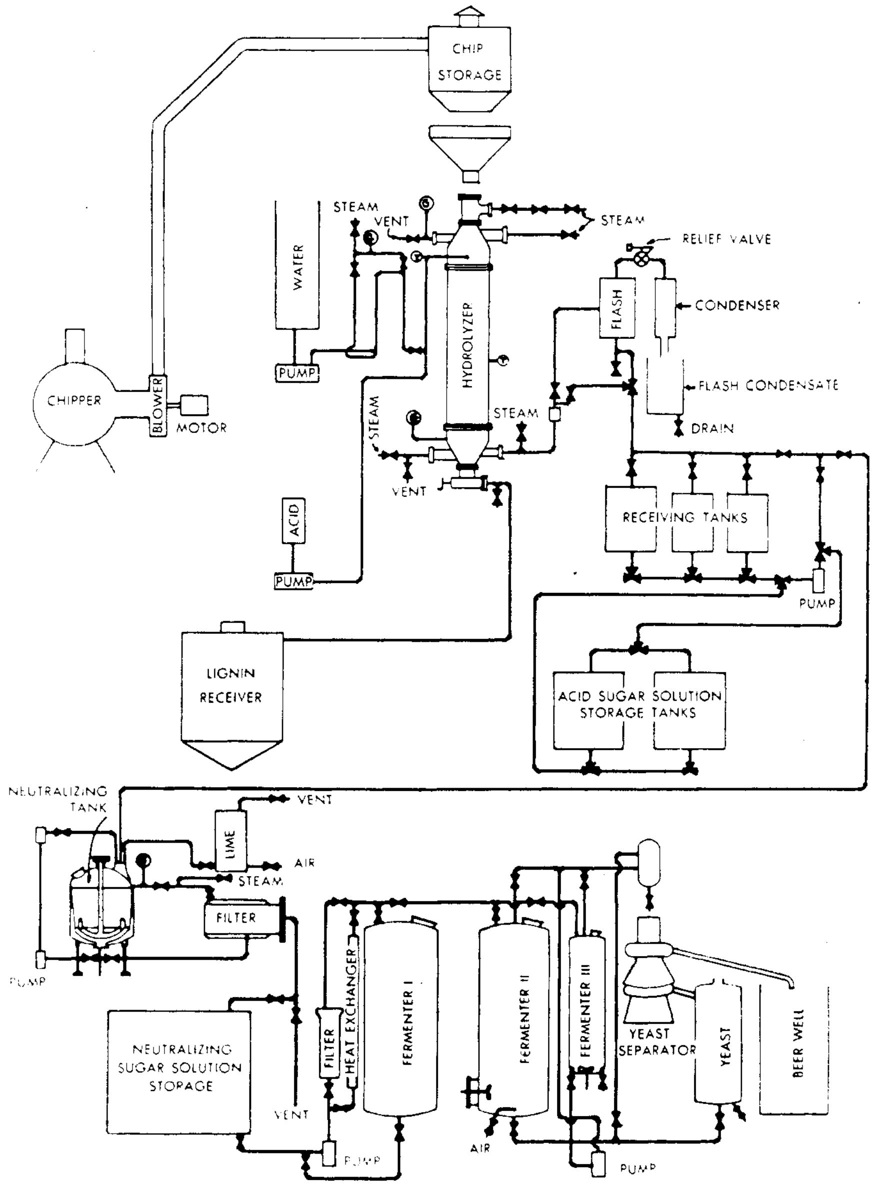

**Figure 1. Equipment for Saccharification of Wood and Fermentation of Wood Sugar Solutions**

to the hydrolyzer, which controls both pumps; a water heater consisting of a jet heater for blowing steam into the water; a jet in the water line for introducing acid; two openings in the top of the digester for introducing acid liquor; a silicon bronze digester, 23 inches in inside diameter (capacity 27 cubic feet), fitted with a reducing cone at the top and a reducing cone and filter screen at the bottom; a flash tank; three receiving tanks fitted with mixers; a lignin receiver; a neutralizing kettle; and storage tanks. The fermentation equipment shown in Figure 1 is discussed in another paper (*7*).

Analytical values were determined by methods reported previously by the Forest Products Laboratory (*3, 16, 17*).

## THE PROCESS

Chipping or hogging is an important part of the process. Particles should be large enough so that flow of dilute acid down through the charge is uniform and rapid, but also small enough so that diffusion of the acid into the chip, and of the sugar out of the chip, is rapid. Douglas fir wood-waste mixtures, containing 25 to 30% shavings, 25 to 30% sawdust, and 40 to 50% slabs and edgings, hogged so that particles measured between $^1/_4$ and 1 inch long, were satisfactory. The hogged wood contained 35 to 50% bark. A hog chipper provided satisfactory material when the larger sizes were screened out and sent through again. Green wood waste containing 30 to 50% of its weight as moisture appeared more satisfactory than dry material because infusion of acid was more rapid.

The digester had to be charged so that the wood waste was evenly distributed with respect to fine and coarse material, was uniformly packed and of such density that full use could be made of the acid as a hydrolyzing and extracting medium, and so that plugging of the digester did not result. Variations in the amount of bark made possible variations in the extent of packing the charge. Because of the corky nature of bark, charges with large amounts of bark could be packed more heavily into the digester without plugging it. It proved helpful but not essential to place some coarse material on the bottom of the digester to provide a bed for easy flow of the sugar solution through the filtering screen at the bottom. These conditions were attained when a charge of mixed wood waste was allowed to flow into the heated hydrolyzer until the latter was completely full; a quick-opening flange cover was then put in place and high pressure steam (150 pounds per square inch) was applied rapidly on top of the charge, with vents open at the bottom until a gage at the top of the digester showed a pressure of 10 pounds. The steam valve was then closed and the steam allowed to flow through the charge until no pressure showed on the gage. The cover was then removed, more of the wood waste mixture added, and the packing with steam repeated. Charges of 400 to 500 pounds on a dry basis, with 25 to 35% of bark, were introduced under these conditions. The heaviest charges were used when the largest amount of bark was present. Most of the air in the chips was removed, and some heating resulted, as the steam passed over the chips. In order to remove more air and continue the heating, a top vent was opened and steam was introduced at the bottom of the digester. When steam flowed from the top vent, the vent was closed and the steam was allowed to flow into the digester until a pressure of 50 pounds was reached.

Dilute acid at 150° C. was introduced into the heated digester in such concentrations that, by the time an amount of dilute acid equivalent to half the dry weight of the charge had been introduced, the acid concentration of all the water present was 0.5 to 0.6%. A charge of wood waste, containing 45% of its weight as moisture after it had been packed and heated with steam at 50 pounds per square inch, contained approximately 600 pounds of moisture and, therefore, required 200 pounds of 2.0% sulfuric acid to bring the concentration to 0.5%. After this stronger acid had been introduced, sufficient heated sulfuric acid of 0.5 to 0.6% concentration was introduced to bring the ratio of total dilute acid to dry wood substance to about 3 to 1. Under one set

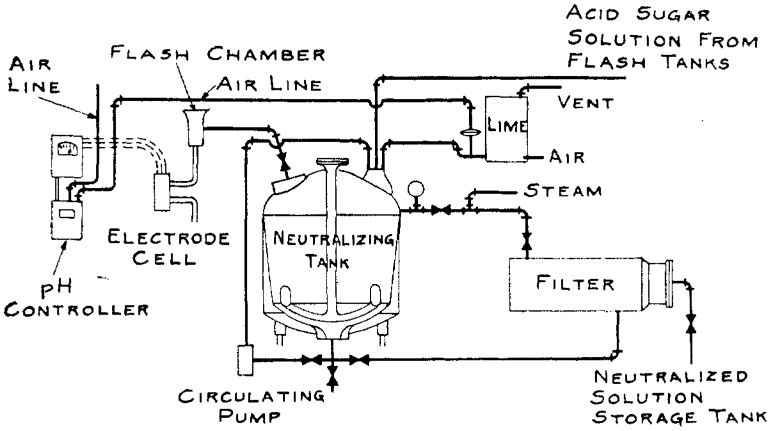

**Figure 2. Equipment for Neutralization of Wood Sugars**

of conditions this acid was introduced rapidly so as to flood the charge and then allowed to digest for approximately 20 minutes. Under another set of conditions, the acid was pumped in at the rate of 20 pounds per minute.

Following this initial charge, heated acid (concentration, 0.5 to 0.6%) was pumped in continuously at a rate of 20 pounds per minute. The temperature of the incoming acid was adjusted by an automatic controller so that it increased approximately 5° for each 10-minute period until 185° C. was reached; the run was continued at that temperature until it was complete. This procedure was also compared with the batch procedure for introducing acid used in previous runs (*6*).

While the continuous pumping was in progress, a flow controller in the acid-sugar solution line was opened so that 20 to 25 pounds of the solution were removed per minute.

The continuous introduction of acid and continuous removal of sugar solution provided a means of rapid hydrolysis and removal of the solution. Initial concentrations of reducing sugar were as high as 10%. Concentrations decreased as the hydrolysis continued. After about 2 hours of continuous pumping, the concentration fell to about 1%, and at this point the introduction of acid was stopped. Sugar solution was removed as long as it flowed freely from the hydrolyzer. In most cases it continued to flow for about 15 minutes, after which a large valve in the bottom of the digester was opened to discharge the lignin into a lignin receiver.

The sugar solution withdrawn from the hydrolyzer was passed into an expansion chamber, or flash tank, to release the steam and drop the pressure to about 30 pounds per square inch. The drop in pressure was accomplished by a pressure-regulating relief valve. This valve allowed the steam and vapors of methanol and furfural to pass through a heat exchanger or condenser, where they gave up heat which was used to heat the water for the dilute acid.

From the flash tank the sugar solution flowed continuously under a pressure of 30 pounds per square inch to a pressure-neutralizing tank (Figure 2) at the rate of 16 to 20 pounds per minute. When approximately 100 pounds of solution had flowed into the tank, the automatic pH controller was started; lime was thereby introduced under air pressure from a lime tank through a proportioning valve. The controller was actuated by a stream of liquid, which was removed from the neutralizing tank, flashed to atmospheric pressure, and allowed to flow over the electrodes in a specially designed cell. The amount of solution required was approximately 100 cc. per minute. This sugar solution was collected and introduced in the neutralizing kettle prior to the next run. When the pH of the solution in the neutralizing kettle had reached the desired value, a valve to the filter was opened; this allowed the same amount of solution to be removed as was introduced. Variations in pH were usually less than 0.1 unit during neutralization of the sugar solution for a run of about 3 hours.

Attempts were made to neutralize the sugar solution continuously in a pipe line at atmospheric pressure, without the use of a holding tank. The lag in the neutralization with lime was too great to permit satisfactory operation of the pH controller. Tests with sodium hydroxide gave satisfactory operation.

TABLE I. COMPOSITION OF AND PRODUCTS FROM DOUGLAS FIR SAWMILL WASTE

| | Composition, % | | Yield of Hydrolysis Products | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | At 0.5% or less concn. of reducing sugar | | | At 5% concn. of reducing sugar[a] | | |
| Form of Wood | Potential reducing sugar content | Potential fermentable sugar | Total reducing sugar, % | Fermentable reducing sugar, % | Alcohol, gal./ton | Total reducing sugar, % | Fermentable reducing sugar, % | Alcohol, gal./ton |
| Bark | 37.5 | 26.4 | 18.4 | 11.2 | 16.9 | 15.3 | 9.3 | 13.9 |
| Sawdust (13.5% bark) | 63.2 | 53.4 | 44.6 | 37.1 | 55.5 | 41.6 | 34.6 | 51.9 |
| Slabs, bark-free | 67.5 | 57.0 | 48.9 | 40.6 | 61.0 | 39.0 | 32.1 | 48.5 |
| Slabs, mill-run (35% bark) | 56.3 | 47.4 | 38.7 | 31.0 | 45.0 | 30.4 | 24.4 | 36.6 |
| Hog fuel G, select removed (52% bark) | 50.9 | 42.1 | 35.3 | 28.3 | 42.5 | 29.2 | 23.4 | 35.1 |
| Shavings[b] | 67.6 | 57.1 | .. | .. | .. | .. | .. | .. |

[a] Except in case of bark, where hydrolysis was discontinued when concentration of reducing sugar being removed was 1% or less.
[b] Pilot plant hydrolysis not carried out because of inability to charge sufficient amounts in the digester.

TABLE II. HYDROLYSIS OF DOUGLAS FIR SAWMILL WOOD WASTE USING BATCH ADDITION OF DILUTE ACID[a]

| | | | | | | | | Yield[b] | |
|---|---|---|---|---|---|---|---|---|---|
| Run No. | Kind of Wood Waste | Dry Wood, Lb. | Bark-Free Wood, Lb. | Hydrolysis Time, Hr. | Sulfuric Acid[b], % | Reducing Sugar Solution, Lb. | Solution Concn., % | Reducing sugar, % | Alcohol, gal./ton |
| 176 | Hog waste | 455 | 296 | 3.4 | 6.6 | 2800 | 5.00 | 47.3 | 59.1 |
| 178 | Hog waste | 500 | 324 | 3.3 | 6.9 | 3200 | 4.75 | 47.0 | 58.8 |
| 179 | Sawdust | 430 | 370 | 3.0 | 6.3 | 3250 | 4.97 | 43.8 | 54.9 |
| 194 | Sawdust | 420 | 364 | 2.9 | 6.1 | 3305 | 4.90 | 44.6 | 55.6 |
| 220 | Sawdust | 350 | 302 | 2.9 | 7.6 | 2950 | 4.82 | 47.0 | 58.7 |
| 221 | Sawdust | 370 | 320 | 3.0 | 6.9 | 3060 | 5.10 | 49.0 | 61.0 |
| 187 | Hog waste[c], 35% shavings, 65% | 354 | 300 | 3.0 | 7.0 | 3250 | 4.53 | 45.2 | 56.5 |
| 188 | Hog waste[c], 54% shavings, 46% | 450 | 366 | 3.2 | 6.5 | 3550 | 4.80 | 46.7 | 58.3 |
| 217 | Hogged wood waste[d] | 400 | 337 | 3.0 | 7.3 | 3200 | 4.72 | 45.0 | 57.5 |
| 218 | Hogged wood waste[d] | 409 | 340 | 3.0 | 6.6 | 3200 | 4.73 | 44.5 | 55.6 |
| 232 | Slab wood chips and sawdust | 399 | 332 | 3.1 | 6.6 | 3130 | 5.10 | 48.0 | 60.0 |

[a] Hydrolysis was discontinued when total hydrolyzate averaged approximately 5.0%.
[b] Values based on bark-free wood.
[c] Hogged sawmill waste containing 50.9% bark.
[d] Containing 40% shavings and 20% sawdust.

Table III. Continuous Hydrolysis of Douglas Fir Wood Waste, with Continuous Addition of Dilute Acid and Continuous Removal of Sugar Solution

| Run No. | Wood Waste, Lb. |  | Bark-Free Wood[a], Lb. | Time, Hr. | Acid[a], % | Soln., Lb. | Reducing Sugar Concn.[a], % | Reducing Sugar Yield[a], % | Alcohol[a], Gal./Ton |
|---|---|---|---|---|---|---|---|---|---|
|  | Hog fuel | Shavings |  |  |  |  |  |  |  |
| 263 | 282 | 108 | 294 | 2.6 | 6.5 | 2400 | 4.95 | 40.5 | 50.5 |
| 264 | 292 | 102 | 294 | 2.6 | 6.8 | 2400 | 4.67 | 38.2 | 47.6 |
| 265 | 300 | 123 | 321 | 2.5 | 7.5 | 2700 | 4.56 | 38.3 | 47.9 |
| 266 | 320 | 151 | 362 | 3.0 | 5.5 | 2800 | 4.55 | 36.5 | 45.7 |
| 267 | 282 | 170 | 364 | 2.7 | 5.0 | 2880 | 5.10 | 40.3 | 50.3 |
| 269 | 310 | 148 | 363 | 3.0 | 6.5 | 3250 | 4.87 | 43.7 | 54.6 |
| 273 | 255 | 144 | 315 | 2.5 | 5.7 | 2600 | 5.08 | 41.9 | 52.4 |
| 274 | 231 | 141 | 293 | 2.7 | 7.4 | 2300 | 5.20 | 40.6 | 50.9 |
| 275 | 235 | 146 | 301 | 2.3 | 5.2 | 2530 | 5.30 | 44.6 | 55.7 |
| 276 | 246 | 151 | 316 | 2.7 | 6.3 | 2830 | 5.03 | 45.0 | 56.2 |
| 278 | 230 | 142 | 294 | 2.7 | 6.3 | 2800 | 4.83 | 46.0 | 57.5 |
| 284 | 235 | 143 | 296 | 2.8 | 5.9 | 2800 | 4.36 | 41.1 | 51.5 |
| 285 | 280 | 147 | 329 | 3.0 | 4.6 | 2800 | 4.77 | 40.5 | 50.6 |
| 286 | 283 | 109 | 293 | 2.8 | 6.1 | 2440 | 4.88 | 40.6 | 50.8 |
| 287 | 290 | 131 | 319 | 3.0 | 5.7 | 2800 | 4.96 | 43.6 | 54.5 |
| 288 | 282 | 120 | 303 | 2.7 | 5.8 | 2400 | 5.00 | 39.7 | 49.6 |
| 289 | 294 | 104 | 295 | 2.7 | 5.8 | 2400 | 4.30 | 35.0 | 43.8 |
| 292 | 500 | ... | 326 | 2.8 | 5.5 | 2800 | 5.00 | 42.9 | 54.6 |
| 293 | 278 | 151 | 331 | 3.0 | 6.5 | 2800 | 5.04 | 42.6 | 53.3 |
| 294 | 273 | 165 | 344 | 3.0 | 6.0 | 2800 | 5.00 | 40.7 | 51.0 |
| 295 | 298 | 137 | 330 | 2.8 | 5.7 | 2800 | 4.86 | 41.2 | 51.6 |
| 296 | 290 | 140 | 329 | 3.0 | 6.2 | 2800 | 4.75 | 40.5 | 50.6 |

[a] Values calculated on the basis of bark-free wood.

Neutralization of the sugar solution, under pressure and in batches, was carried out satisfactorily with the same equipment used for continuous neutralization. Such batch neutralizations, however, required either the use of a holding tank to store the solution under pressure or the flashing of acid-sugar solution to atmospheric pressure before storage; the solution then had to be reheated before it could be neutralized and filtered.

Calcium sulfate, which had separated from the solution under pressure, was removed by passing the solution (still under pressure) through a steam-jacketed leaf filter. The sulfate content, which would have been 2100 parts per million at 100° C. and atmospheric pressure, was reduced to an average of about 650 p.p.m. by neutralization and filtration under a steam pressure of 30 pounds per square inch. This low value for calcium is expected to aid greatly in preventing scale formation in the stills during alcohol distillation.

After they had been filtered under pressure, the neutralized sugar solutions were cooled to 30° C. by flashing. A brown precipitate separated from the solution as it cooled. When this precipitate was removed, the solution was a clear amber color and contained approximately 5% reducing sugar.

The procedure described as the Madison wood sugar process was used to hydrolyze the carbohydrate portion of Douglas fir wood waste from sawmills operating in the Eugene, Oreg., area. Representative samples of bark, bark-free hogged slabs, hogged mill-run slabs and edgings, shavings, sawdust, and hogged mill waste from which the best slabs had been removed were analyzed for bark content, potential sugar content, and potential fermentable sugar content; the samples were then subjected to the pilot plant batch hydrolysis procedure described in previous reports (*3*, *6*).

### CONDITIONS

Two sets of conditions were employed. In one, the hydrolysis was continued until the concentration of the sugar being removed was 0.5% or less. In the other, the hydrolysis was continued until the average reducing-sugar content of the total hydrolyzate was approximately 5.0%. In the case of bark the latter hydrolysis was discontinued when the concentration of the reducing sugar being removed was 1.0% or less, because at no time was the concentration of reducing sugar from bark as high as 5.0%. The values for the analysis, hydrolysis, and yields of alcohol from the various samples are given in Table I.

The yield of alcohol from bark was so low that the capacity of the hydrolyzer equipment to produce fermentable sugar was lessened. In order to increase this capacity, several tests were made in which either larger quantities of wood waste were charged into the digester by using higher packing pressures, or shavings or hogged bark-free slab wood were mixed with the hogged mill waste to reduce the average bark content of the total charge. In these tests, in which about 25% of the charge was bark, about 7% of the total alcohol obtained was from the bark. In order to have a uniform basis for comparison, however, the yields of reducing sugar and alcohol are expressed on the basis of bark-free wood. Table II gives the values for the wood waste containing varying amounts of bark and hydrolyzed by batch addition of the dilute acid and batch removal of the sugar solution.

Because of the greater ease of operation and control afforded by the method, several tests were made in which acid was continuously introduced and sugar solution continuously removed throughout the entire hydrolysis period. In most cases sugar solution began to flow from the bottom of the hydrolyzer about 15 minutes after the acid was first introduced. In many cases, the first sugar solutions to come off were only partially hydrolyzed. Values for the hydrolysis of wood obtained with the completely continuous process are given in Table III. Hydrolysis was discontinued when the average concentration of reducing sugar of the total hydrolyzate was approximately 5.0%.

To overcome the tendency toward mere partial hydrolyzation of the first reducing sugar removed, the following changes in procedure were made: (*a*) Two hundred pounds of dilute acid (1.5 to 2% concentration) was rapidly introduced; (*b*) 400 to 600 pounds—the amount of acid of 0.5 to 0.6% concentration required to bring the ratio of dilute acid to wood to 3 to 1—were introduced at a rate of about 12 gallons per minute; (*c*) the reaction was allowed to continue for 30 minutes from the time the first acid was introduced, and meanwhile the temperature was maintained at 150° C. by admitting steam at the bottom of the digester; (*d*) after this reaction period the pumps were set to introduce 20 pounds of acid (0.5 to 0.6% solution) per minute, and the controller was set to increase the temperature 0.5° per minute until 185° C. was reached; at this temperature the run was continued until it was complete. The sugar solution was removed continuously through a flow controller at the same rate the acid was introduced. The hydrolysis was discontinued when the average reducing sugar concentration of the total hydrolyzate was about 5.0%. The solutions were neutralized under pressure with lime, cooled to 30° C., adjusted for pH to the final desired value, and then fermented. The procedure for fermentation is given in another report (*7*), and the results of hydrolysis tests and fermentations are presented in Table IV.

### APPLICATION TO COMMERCIAL PLANTS

Assuming that the values in the last twenty-two runs of Table IV are representative of the charging capacity of the digester and of the mixture of wood waste available, an average charge of 319 pounds of dry, bark-free wood waste can be placed in a 27-cubic-foot digester. This corresponds to a charge of 11.8 pounds of dry, bark-free, mixed wood waste per cubic foot. The average alcohol yield from the sugars produced by hydrolysis corresponded to 64.5 gallons per ton of dry, bark-free wood, or 0.38 gallon per cubic foot of digester space.

These values may be used in determining the capacity of the wood hydrolysis plant being constructed by the Defense Plant Corporation at Springfield, Oreg., formerly sponsored by the War

Table IV. Hydrolysis of Douglas Fir Sawmill Wood Waste, Using Batch Addition of First Charge Followed by Continuous Introduction of Acid and Continuous Removal of Sugar Solution

| Run No. | Hog Fuel B (35% Bark), % | Shavings, % | Dry Wood, Lb. | Bark-Free Wood, Lb. | Hydrolysis Time, Hr. | Acid, %[a] | Reducing Sugar Weight, Lb. | Reducing Sugar Concn., % | Yield, Bark-Free Wood, %[a] | Alcohol Concn., G./100 Ml. | Yield, Gal./Ton[a] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 243 | 100 | .. | 451 | 294 | 3.0 | 5.8 | 3020 | 5.05 | 52.0 | 1.96 | 65.0 |
| 245 | 100 | .. | 465 | 302 | 3.0 | 6.2 | 3000 | 5.08 | 50.3 | 1.97 | 63.0 |
| 246 | 75 | 25 | 448 | 328 | 3.1 | 5.3 | 3100 | 5.18 | 48.8 | 2.03 | 61.0 |
| 249 | 75 | 25 | 470 | 340 | 3.0 | 4.5 | 2900 | 5.25 | 45.0 | 2.04 | 56.0 |
| 250 | 72 | 28 | 478 | 344 | 2.7 | 4.9 | 2700 | 5.65 | 45.6 | 2.20 | 57.0 |
| 252 | 50 | 50 | 460 | 370 | 3.0 | 5.0 | 2980 | 5.15 | 41.5 | 2.01 | 52.0 |
| 253 | 50 | 50 | 436 | 357 | 2.8 | 5.4 | 3100 | 4.90 | 42.5 | 1.90 | 53.0 |
| 254 | 52 | 48 | 434 | 350 | 2.9 | 5.6 | 3100 | 5.40 | 48.0 | 2.12 | 60.0 |
| 255 | 54 | 46 | 447 | 364 | 3.1 | 5.6 | 3200 | 5.48 | 48.2 | 2.14 | 60.2 |
| 256 | 54 | 46 | 447 | 364 | 3.1 | 5.6 | 3300 | 5.18 | 47.0 | 2.01 | 58.9 |
| 257 | 100 | .. | 444 | 290 | 2.9 | 7.0 | 3200 | 4.85 | 53.3 | 1.89 | 65.6 |
| 262 | 70 | 30 | 385 | 293 | 2.8 | 6.7 | 3000 | 5.01 | 51.5 | 1.95 | 64.3 |
| 268 | 62 | 38 | 457 | 358 | 3.2 | 6.3 | 3640 | 4.96 | 50.5 | 1.94 | 63.2 |
| 270 | 56 | 44 | 380 | 314 | 2.6 | 5.9 | 3100 | 4.95 | 49.0 | 1.93 | 61.3 |
| 271 | 59 | 41 | 383 | 313 | 2.7 | 6.5 | 3000 | 5.06 | 48.5 | 1.97 | 60.7 |
| 277 | 65 | 35 | 380 | 296 | 2.7 | 6.7 | 3100 | 4.92 | 51.5 | 1.92 | 64.3 |
| 279 | 70 | 30 | 417 | 319 | 2.8 | 7.0 | 3500 | 5.00 | 54.8 | 1.95 | 68.5 |
| 280 | 65 | 35 | 412 | 322 | 2.9 | 7.0 | 3500 | 5.00 | 54.5 | 1.95 | 68.0 |
| 281 | 64 | 36 | 405 | 318 | 2.8 | 6.5 | 3500 | 4.80 | 52.7 | 1.87 | 66.0 |
| 282 | 67 | 33 | 392 | 302 | 2.8 | 6.8 | 3200 | 4.85 | 51.4 | 1.89 | 64.2 |
| 283 | 67 | 33 | 386 | 299 | 2.5 | 6.2 | 3200 | 5.10 | 54.5 | 1.99 | 68.2 |
| 290 | 67 | 33 | 415 | 319 | 2.8 | 6.8 | 3200 | 5.00 | 50.2 | 1.95 | 62.7 |
| 291 | 72 | 28 | 450 | 339 | 2.5 | 5.5 | 3200 | 5.30 | 50.2 | 2.06 | 62.7 |
| 297 | 68 | 32 | 405 | 308 | 2.7 | 7.0 | 3120 | 5.04 | 50.8 | 1.96 | 63.5 |
| 298 | 49 | 51 | 387 | 303 | 2.9 | 7.2 | 3300 | 5.10 | 55.5 | 1.99 | 69.0 |
| 299 | 67 | 33 | 449 | 343 | 2.7 | 6.4 | 3650 | 4.80 | 50.8 | 1.87 | 63.5 |
| 302 | 70 | 30 | 391 | 285 | 2.6 | 7.3 | 3200 | 4.85 | 54.5 | 1.89 | 68.2 |
| 303 | 71 | 29 | 407 | 305 | 2.8 | 6.8 | 3315 | 4.90 | 53.1 | 1.91 | 66.5 |
| 304 | 70 | 30 | 401 | 301 | 2.6 | 6.8 | 3100 | 5.10 | 52.5 | 1.98 | 65.5 |

[a] Value calculated on dry, bark-free wood.

Production Board and now by the U. S. Department of Agriculture.

The plant consists of five digesters, each with a capacity of about 2000 cubic feet. Each digester will hold 11.8 tons of dry, bark-free wood, or 15.8 tons of the dry wood substance. In most cases moisture constituted about 40% of the total weight of the material charged into the digester; the usual charge, therefore, including moisture, will be about 26.5 tons.

Loading equipment and valves are designed to charge and pack the digesters in about 30 minutes, and steaming and heating will require about another 30 minutes. Assuming the rate of flow of the initial charge of acid downward through the bed of chips to be a function of the depth of the bed, and the rate per foot traveled to be the same as in the 27-cubic-foot digester, 40 minutes will be required for the liquid to pass through the charge in the 2000-cubic-foot digester instead of the 11 to 12 minutes required in the pilot plant digester. The rate of hydrolysis of the cellulose is a function of acid concentration, time, and temperature (*15*) and is independent of the size of the digester. Since the introduction of acid and removal of sugar solution are continuous, no extra time will be needed for the flow of hydrolyzing liquid through the charge after the run is started and until the pump is stopped, when another 40 minutes will be required to drain the liquid from the digester.

The over-all increase in time necessary because of the larger size of the commercial digester should, therefore, be only 55 to 60 minutes. The average time required for the last twenty-two runs listed in Table IV was about 2 hours and 50 minutes from the time pumping started until the lignin was discharged from the digester. This indicates that 4 hours should be sufficient for the same operation in the large digester and that, including the charging of the digester and heating, a 5-hour operating cycle will be possible. Such conditions will allow no time for repairs and for the possible need of removing some lignin from a digester. It appears, however, that the latter possibility has been eliminated because, in about a hundred runs using continuous pumping with Douglas fir mill waste, the equipment never failed to blow the lignin completely from the digester. Even allowing an hour for such exigencies, or a 6-hour operating cycle, hydrolysis of twenty charges of wood will be possible per day.

The yield of alcohol obtained in the last twenty-two runs of Table IV indicates that 760 gallons of alcohol can be produced from the sugars from one digester charge, or 15,200 gallons per 24-hour day and 5,472,000 gallons per 360-day year for the whole plant. If a 5.5-hour cycle is possible, allowing 30 minutes down time per run, the output will be 16,550 gallons per day, or 5,950,000 gallons per year.

For the production of 15,200 gallons of alcohol per day, 236 tons of dry, bark-free wood or 310 tons of dry wood with bark will be required. If the 5.5-hour operating schedule is used and 260 tons of dry, bark-free wood produce about 16,550 gallons of alcohol per day, 350 tons of dry wood substance with bark will be required.

Automatic control of the introduction of the acid and removal of the sugar solution, as well as automatic control of neutralization, makes possible better operation with less manpower. Improvements in a process for continuous fermentation, which will be published in another report, make possible savings in manpower and better distribution of the utilization of equipment for that portion of the operation.

## COST OF ALCOHOL PRODUCTION

There are many unknown factors in the cost of operating a wood hydrolysis plant. Assuming the values for chemicals required and the yields of products obtained in the pilot plant to be representative of values possible in a large plant, the cost of chemicals for processing one ton of dry, bark-free wood waste can be tabulated as follows:

| Chemical | Pounds Required per Ton of Wood | Value of Chemical per Ton | Cost of Chemical per Ton of Wood |
|---|---|---|---|
| Acid | 130 | $20.00 | $1.30 |
| Lime | 100 | 20.00 | 1.00 |
| Nutrients<br>Caustic<br>Permanganate | | | 0.20 |
| | | | $2.50 |

Based on a yield of 64.5 gallons per ton of wood, the cost of chemical per gallon of alcohol produced will be 3.9 cents.

An average delivered price of 2 dollars per ton of dry, bark-free wood is assumed. Wood with bark and moisture is to be used for the process, but since moisture and bark yield little or no alcohol, the processor does not expect to pay for them. The presence of moisture and bark increases delivery costs and limits the distance wood waste may be transported; 2 to 2.5 tons of material must be delivered at the plant for each ton of dry, bark-free wood. The cost of wood per gallon of alcohol produced on this basis is 3.1 cents.

The calculated labor requirement for the plant is sixty-five men. On the basis of present wage scales and other labor overhead, such as insurance, social security, and other expenses, the cost for labor and labor overhead will be 4 cents per gallon. Other costs, such as electric power, water, maintenance, overhead, supervision, and extra wood waste that may be needed for the power plant are estimated to be 3.7 cents per gallon.

These values bring the cost of production, exclusive of plant amortization, to 14.7 cents per gallon. No credit is taken in these calculations for by-products. Assuming that it is desirable to pay off as much of the cost of the plant as possible while alcohol prices remain high, and allowing 3% interest on the investment, the retirement of the principal in about four years for a plant producing 5,472,000 gallons per year will cost 13.7 cents per gallon. Amortization in seven years with a production of 5,950,000 gallons will cost 7.6 cents per gallon, bringing the cost of production to a value between 22.3 and 28.4 cents per gallon, exclusive of any income from by-products.

## BY-PRODUCTS

The daily by-products of the process are about 100 tons of lignin (dry basis), 33 tons of calcium sulfate dehydrate, 6000 pounds of furfural, 5000 pounds of methanol, and about 11.8 tons of nonfermentable sugars dissolved in about 1800 tons of water. Ready markets are available for the furfural and methanol, and income from these products can reduce the cost chargeable to the alcohol.

Until other markets are developed, it is expected that the lignin will be used as boiler fuel. On a dry basis this lignin has a value of about 10,500 B.t.u. per pound. Normally the product will be obtained from the process with about 50.0% moisture. The sulfur content due to sulfuric acid will be about 0.16%. This value may be lowered by washing if a lower acid content is desired. It is believed that the lignin will supply most of the fuel required. This lignin is being tested as a resin extender, for plastics, as a carrier of chemicals for soils improvement, and as a source of new chemical products. If it is found that lignin has a higher value in some of these or other fields than it has as fuel, it, too, may be used to reduce the cost of alcohol.

Calcium sulfate has value in some localities as a source of lime and sulfur for the soil. It is expected that its value for this purpose will pay for its removal and transportation.

The 11.8 tons of nonfermentable sugars are largely xylose. Pilot plant experiments on the growing of fodder yeast on these sugars are in progress and show some promise. This material may prove to be an undesirable source of stream pollution if it is not used.

## OTHER PLANTS

There has been a great deal of interest in the possibility of producing alcohol from smaller quantities of wood waste, and for this reason the effect of plant size on production costs should be considered. The cost of acid, lime, steam, wood waste, water, and power may differ in various parts of the country because of variations in distance from the point of production. In general, however, these variations are small and depend on the amount processed. That charge, therefore, may be assumed to be fixed. The costs for labor and plant will differ according to plant size. Labor required for a wood hydrolysis plant depends on the number of operations to be performed rather than on the size of the equipment and, therefore, is practically independent of size. In a plant producing one fourth the amount of alcohol, the cost for labor is approximately four times as great per gallon of alcohol produced.

It is possible that a plant built under peacetime conditions will cost less, and also that many of the simplifications found in the pilot plant operations will result in a reduction in cost of equipment; in general, however, size reduction does not result in a proportionate reduction in the cost of equipment.

At present it is not possible to forecast the postwar price of alcohol. Assuming, however, that the cost of production is similar to that under prewar conditions, alcohol must be produced for 30 cents per gallon or less in order to compete with other sources. Under such conditions a plant processing approximately 150 tons of wood waste daily would be about the smallest plant that could operate with a profit, unless valuable uses could be found for lignin.

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