UNIVERSITY OF IDAHO
AGRICULTURAL EXPERIMENT STATION

Departments of Agricultural Engineering
and Agricultural Chemistry

The Production of Ethyl Alcohol From Cull Potatoes and Other Farm Crops

A Review of the Status of Alcohol Production and Utilization, and a Report of the Operations of the Experimental Alcohol Plant at Idaho Falls

By

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Acknowledgement

The Idaho Falls Experimental Plant operations were conducted by Marvin Aslett, Plant Superintendent; Gerwin Taylor, Plant Chemist; Eugene Graham; and Anton Pedersen.

The laboratory scale research program at Moscow, preceding the erection of the experimental plant, was carried on by Hobart Beresford, the late H. P. Magnuson, R. S. Snyder, Marvin Aslett, Wilson Bow, Gerwin Taylor, Jefferson B. Rodgers, and Woodrow Arrington.

The experimental plant was authorized and funds for its construction provided by the Idaho legislature in 1937 (H. B. 171). The Idaho Falls Chamber of Commerce and the Idaho Advertising Commission gave financial aid for plant improvements and for the construction of experimental equipment. The Idaho legislature appropriated funds for plant operations in 1939, and the City of Idaho Falls furnished electric power and water free of charge during the entire period of operations. The Idaho Falls Potato Growers, Inc., donated 300 tons of cull potatoes during the 1939-1940 season. The Utah-Idaho Sugar Company donated approximately 30 tons of beet molasses.

Industrial Alcohol Plant, Idaho Falls Laboratory of the Idaho Agricultural Experiment Station, receiving cull potatoes.

Three hundred tons of potatoes were supplied the project through the cooperation of the Idaho Falls Potato Growers, Inc.

The Production of Ethyl Alcohol from Cull Potatoes and Other Farm Crops

By
HOBART BERESFORD and LEO M. CHRISTENSEN*

THIS BULLETIN reports the results of four years' research financed by special grants by the Idaho legislature for studies on the methods of producing industrial ethyl alcohol from farm crops, particularly from cull potatoes. Prior to 1936, about four years' research on a smaller scale had been done in the Departments of Agricultural Engineering and Agricultural Chemistry. Progress reports have been made from time to time, but this is the first complete report of the eight years' research activity.

The first three sections present brief reviews of the recent literature pertaining to present or potential markets for ethyl alcohol, and to current processing methods and byproducts. Research leading to the development of an improved manufacturing process is briefly described, and a record of the operations of the experimental plant at Idaho Falls is next presented, following which cost statements are given.

The broad economic significance of power alcohol as it relates to agriculture has been adequately described in recent United States Department of Agriculture (2) and Iowa State College bulletins (4), and is therefore given only small attention in the present report.

The Markets for Ethyl Alcohol

The manufacture of ethyl alcohol is the oldest of the organic chemical industries and today is more widely applied than any other. Most of the alcohol is made by the fermentation of various farm products, but in recent years a small production has been developed using ethylene from petroleum cracking still gases, and still smaller amounts have been made from acetylene produced from coke and lime. There are five principal markets or uses for ethyl alcohol:

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* Agricultural Engineer and Agricultural Chemist, Agricultural Experiment Station, respectively

1. As an intermediate in chemical manufacture, where it is used in the production of acetic acid, ether, ethylene, ethyl acetate, ethyl cellulose, many dyes and medicinals and other chemical products;
2. As a solvent, in paints, varnishes, lacquers, flavoring extracts, and many medicinal preparations;
3. As a fuel, for lamps and small stoves, and for internal combustion engines;
4. As an antifreeze, particularly in automobile radiators;
5. As a beverage.

In the United States the total annual production of industrial alcohol, which does not include that used in beverages, averages more than 100 million gallons per year. It is thus one of the large chemical industries and is a particularly important one because ethyl alcohol has so many uses.

Since most of the alcohol is produced from farm crops, the farmer has a real interest in the industry, and anything that can be done toward expanding the markets for ethyl alcohol is of interest to him. So close is the relationship between agriculture and alcohol manufacture that in most of the central European countries the alcohol plants are largely farmer owned. These plants ordinarily make a crude grade of alcohol which is shipped to central refining plants where it is prepared for market. It has been reported that at one time there were 35,000 such farmer-owned plants in Germany alone (3).

There has never been in the United States a development like that in the central European countries, although before 1914 alcohol plants were generally small, located in the farm belt, largely in Illinois, Indiana, and Ohio, and used locally grown crops, usually corn. During the World War* the great increase in the demand for alcohol in the manufacture of munitions and aircraft and the large temporary European demand for corn and wheat made it necessary to expand the industry on the basis of large factories located along the Atlantic seaboard and operated with blackstrap molasses imported from the West Indies and South and Central America. At the end of the war, these large companies continued to operate and were able to supplant the smaller companies of the Midwest. They continue to make most of the industrial alcohol used in this country, using nearly all of the available blackstrap molasses. In addition to these factories, there are smaller plants in Louisiana and California using domestic and imported molasses.

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* Demand for alcohol is again increasing rapidly as the defense program develops. Shortage of molasses and lack of tankers to haul it have created a new interest in the use of domestic crops in the industry. The U. S. Department of Agriculture has decided to sell 20,000,000 bushels of its surplus corn for this purpose.

Many people have thought that the American farmer could well utilize the alcohol industry as a market for surplus and low-grade grains and tubers. Naturally, interest in such a program has always been greatest in years when bountiful crops have reduced farm product prices. But nearly everyone has at the same time realized that domestic alcohol production cannot be expanded until there is also an increased market for it. Thus interest has first concentrated on the possibilities for new markets.

One of the reasons advanced for the repeal of the prohibition laws was that the beverage alcohol industry would use large amounts of farm products. It is generally considered, however, that further increase in beverage alcohol consumption is unlikely, and there may even be a reduction in consumption. Certainly it does not seem probable that this use provides the enlarged market farmers are seeking.

There is no evidence of any development in the solvent field likely to increase the demand for ethyl alcohol. In fact, competing products are now and probably will continue to cut into the use of alcohol in this market. Recently manufacturers of flavoring extracts have broadcast an appeal for research on solvents that might replace ethyl alcohol in these preparations. The reason for such an appeal is that the federal laws and regulations have been made so much more stringent since the increases in the tax on beverage alcohol that it is sometimes inconvenient to use it. In other cases improved synthetic solvents better suited to special uses have found application even though they cost more than does alcohol.

Only a few years ago ethyl alcohol was the principal, almost the only, antifreeze used in automobile radiators; and about one-third of the total production of ethyl alcohol sold into this market. When winter came, the motorist put alcohol in his automobile radiator; now he buys a branded antifreeze that may be ethyl alcohol, ethylene glycol, methyl alcohol, isopropyl alcohol, or some mixture of these. Advertising and other sales costs have become such a large part of the total cost, and raw material such a small part that the original advantage of ethyl alcohol, low cost, has become of little importance. Talk about rust inhibitors, corrosion preventatives, and evaporation retardants has overshadowed consideration of the antifreeze properties. Antifreeze consumption is seasonal, and the amount used per car is small. Thus to obtain a large volume of distribution, it is necessary to advertise in magazines having wide circulation, and such sales campaigns are very expensive. As a matter of common scientific knowledge, ethyl alcohol, isopropyl alcohol, and methyl alcohol are considered equally good antifreeze materials. All can be treated the same way to retard corrosion and evaporation rate. None is in itself corrosive, but since the water used with them is quite apt to be, it has become common practice to include in the alcohol a material or combination of materials designed to reduce any corrosive effect of the mixture.

Thus it is easily possible to make up ethyl alcohol antifreeze preparations fully as good as the highly advertised methyl alcohol and isopropyl alcohol preparations that normally retail at $1.00 per gallon. In fact, several preparations of this type are marketed; but they are not holding their own in the antifreeze markets, not because of any failure to meet the standards of quality but because of failure to meet competitive advertising. Thus this market does not offer much promise of expansion because of the tremendous sums of money needed to meet competitive sales campaigns.

As an intermediate for chemical manufacture, the future for ethyl alcohol seems much brighter. The increasing use of acetic acid and anhydride, the recent development of ethyl cellulose, and many other products using or incorporating ethyl alcohol give encouragement to those who have been working for new markets. Well-equipped and well-financed organizations are carrying on the research and development work. The alcohol industry and the farmer have to solve the problem, though, of making ethyl alcohol available in adequate amounts at a stable and attractive price that can meet competition. Anything that is done toward this end will greatly aid the industries pioneering these new chemical products.

The use of ethyl alcohol as a fuel holds the greatest immediate promise, and it is pertinent that the development of a large production of fuel alcohol will automatically establish the condition favorable to large chemical utilization. It is, therefore, toward the use of ethyl alcohol as a fuel that those interested in an expanded market for ethyl alcohol have turned. And in this field the best approach has seemed to be the use of anhydrous (water-free) ethyl alcohol in blends with gasoline as a fuel for automotive engines.

Power alcohol research was actively undertaken in the United States in 1932, at the University of Idaho and at Iowa State College. The first attention was devoted to studies of alcohol-gasoline blends as fuels for internal combustion engines of the spark ignition-vapor injection type because it is the type most generally used. Tests at the University of Idaho showed conclusively the suitability of such fuels (3). The physical-chemical properties of various blends were studied, and a comprehensive series of tests in a commercial-type test engine were conducted at Iowa State College, whose Committee on the Use of Alcohol in Motor Fuel issued seven progress reports on various phases of the subject (4). The United State Department of Agriculture (2) made a preliminary study of the economic phases.

The Chemical Foundation, a nonprofit educational and research organization of New York City, financed a commercial scale experiment at Atchison, Kansas. Power alcohol was made from a wide variety of farm crops from 1936 to 1938, and a total of nearly 20 million gallons of blended fuel was distributed in the Midwest. The history of this project was reviewed before a Senate Committee hearing in 1939 (5). As an experimental project, a great deal of valuable information and experience was gained. In 1938 an effort was made by a group of interested individuals to put the project on a commercial basis, but the profit margin in the manufacture of the alcohol was insufficient to pay the large sales development costs inherent in the marketing program used, and the company was forced to suspend operations.

The reports from the several state and federal research laboratories are in good agreement, and the following summary of the properties of alcohol-gasoline blends represents the consensus of opinion. Substantially the same conclusions were announced in Sweden between 1925 and 1930, and subsequently confirmed by research workers in England, Germany, and other European countries.

1. Anhydrous ethyl alcohol is miscible with gasoline in all proportions, and such blends remain homogeneous under conditions easily maintained in commercial distribution and use of motor fuels.

2. Blends containing not more than about 25 per cent of anhydrous ethyl alcohol have physical-chemical properties so nearly like those of gasoline they can be used interchangeably with gasoline of equal antiknock value in automotive engines now generally employed without any change in engine adjustment.

3. Used in this manner, power alcohol is a valuable antiknock agent, and thus is not solely a replacement or substitute for gasoline but a material used to improve the antiknock quality of motor fuel.

4. The efficiency with which alcohol burns and its effect of improving the combustion efficiency of the gasoline with which it was mixed result in a specific fuel consumption with the blend as low as, or frequently lower than, that of gasoline of equal antiknock rating even though the heating value of alcohol is only about 70 per cent that of gasoline.

5. Engine operation as regards power output, smooth performance, and other characteristics is generally more satisfactory with alcohol blends than with gasoline, especially in high-compression engines.

6. Alcohol blends burn more completely than does gasoline, yielding less carbon and carbon monoxide.

A sudden change in the physical-chemical properties of alcohol-gasoline blends occurs when the alcohol content is increased much above 25 per cent by volume. If more than 25 per cent of alcohol is to be used, the engine must be specially adjusted to use the chosen blend. Such is the case in racing engines where blends containing 70 per cent or more of alcohol are very generally used because of the great power output such fuels provide. But such blends are of only academic interest to everyday motorists. Careful scientific tests and large-scale commercial distribution have shown that the blends best suited to commercial use in present-day engines are those containing from 5 to 20 per cent of anhydrous alcohol.

With an annual motor fuel consumption now running about 25,000 million gallons per year in the United States, the potential market for power alcohol is thus between 1,250 million and 5,000 million gallons per year. The annual motor fuel consumption in Idaho is approximately 80 million gallons, enough to use between 4 and 16 million gallons of alcohol per year. Translated to grain needed to produce this amount of alcohol, the potential United States market is between 500 and 2,000 million bushels, and the Idaho market is between 1.6 and 6.4 million bushels. In terms of potatoes, the potential markets are 50 to 200 million tons, and 0.6 to 2.4 million tons, respectively.

The blending of anhydrous alcohol with gasoline is a simple mechanical procedure, pouring them together and mixing by stirring. But since gasolines from various sources vary greatly in important characteristics, the closest technical supervision at the blending plant must be exercised to insure entirely satisfactory fuel blends. Volatility characteristics, antiknock value, gum and sulfur contents, and other characters of the gasoline must be closely watched. For this reason it is desirable that blending be done where adequate technical guidance and testing facilities are available. Thus blending may best be done at the refinery, at the alcohol plant, or at central bulk and blending plants.

In addition to the technical aspects of the blending program, the complex traffic regulations and rates also must be taken into account. Broken hauls are to be avoided, especially in case blending-in-transit rates cannot be secured. Natural breaks in transportation, such as a pipe line terminal or a dock where gasoline is transferred from barge to rail or truck units, are examples of breaks that can be used to advantage in blending. Truck movement of gasoline, being more flexible than rail transportation, frequently fits well into a blending program.

To calculate the value of power alcohol in the competitive motor fuel market is not a simple matter, because it is influenced by many factors. In general, the value of power alcohol is the sum of its value as replacement fuel for gasoline and its value as an antiknock agent. Thus its value is determined by the price of the gasoline having an antiknock value equal to that of the blend and by the difference between the price of that gasoline and some lower grade. Only when a specific location, grade of blend to be prepared, and plan of procedure are decided upon can the exact value of power alcohol be calculated.

Since gasolines vary in their response to alcohol addition, as they also vary in their response to other antiknock agents, there are some disagreements among the many reports of the antiknock value of power alcohol. Both the Idaho (1) and the Iowa (4) studies have shown that a value of 140 octane is a conservative average of the various reported data. Using this value, the expected octane number of a blend may be calculated from the per cent of alcohol in the blend and the octane number of the gasoline by use of the following formula:

$$\frac{\begin{pmatrix}\text{Per cent of gasoline}\\ \text{times octane}\\ \text{number of the gasoline}\end{pmatrix} + \begin{pmatrix}\text{Per cent of alcohol}\\ \text{times}\\ 140\end{pmatrix}}{100} = \begin{matrix}\text{Octane number}\\ \text{of the blend}\end{matrix}$$

Thus if a 10 per cent blend is made with a 65 octane gasoline, the expected octane rating of the blend is:

$$\frac{(90 \times 65) \;+\; (10 \times 140)}{100} = 72.5$$

Alcohol and tetraethyl lead may be used together, each exerting its own influence upon the antiknock rating as though the other were not present. This fact, now receiving further investigation, indicates a somewhat more economical way to use power alcohol than to use it alone. Power alcohol and benzene may also be used together, the benzene being about half as effective as ethyl alcohol in raising the antiknock value. Less is known about the combined influence of the two used together. Obviously alcohol, benzene and tetraethyl lead may also be used together.

Three grades of gasoline are generally marketed, not including aviation kinds. These differ from each other primarily in the antiknock values. The lowest grade varies from a low of 40 to a high of 67 octane; the middle or "Regular" grade is generally 72 to 74 octane; and the top or "Premium," 76 to 80 octane. The trend is definitely toward higher values, to meet the requirements of the higher compression pressures which the automotive engineer depends upon to improve fuel economy and engine performance. In general, the difficulty of increasing octane values of motor fuels is the limiting factor in this trend. Aviation fuels vary from 83 to about 90 octane, with 100 octane fuels available in limited amounts.

The increase in antiknock rating is obtained by the use of improved refinery processes, such as crackling, polymerization, or hydrogenation, and by the use of antiknock agents, of which tetraethyl lead is the most generally used. Since tetraethyl lead is a dangerous poison, its use is regulated to safeguard public health. "Regular" grades generally contain 1 to 2 cubic centimeters of tetraethyl lead per gallon, while the "Premium" grades generally contain the full 3 cubic centimeters per gallon allowed by law. As regards the influence upon the antiknock value, the first cubic centimeter of lead added to gasoline is considerably more effective than the second, which in turn is more effective than the third, and so on. This fact imposes rather definite limitations upon the antiknock values that can be obtained in this manner.

Naturally, the extra treatments used to raise the antiknock value of gasoline increase its cost. But because they are more efficiently utilized in the engine, such high antiknock value fuels are worth more to the motorist. The spread between the several grades varies from one area to another and from time to time. Consumer demand and other marketing factors rather than cost of treatment govern the spread.

On the basis of this analysis, the value of alcohol in the competitive market may be calculated. If, in the example above, the 65 octane gasoline costs the blender 5 cents per gallon exclusive of taxes, and he sells the 72 to 74 octane blend at 5¾ cents per gallon on the same basis, the value of the alcohol used to make the 10 per cent blend is:

$$\frac{(100 \times 5.75) - (90 \times 5.00)}{10} = 12.5 \text{ cents per gallon}$$

If gasoline prices are higher, as in Idaho, but the spread remains the same as in the above example, the value of the alcohol is higher. Thus, if the 65 octane gasoline costs 12 cents per gallon and the 72 to 74 blend sells at 12¾ cents, the value of the alcohol is:

$$\frac{(100 \times 12.75) - (90 \times 12.00)}{10} = 19.5 \text{ cents per gallon}$$

If the spread between the grades widens, the value of the alcohol is increased. Thus if the lower grade costs only 4½ cents and the 72 to 74 blend sells at 5¾ cents, the value of the alcohol becomes:

$$\frac{(90 \times 5.75) - (90 \times 4.50)}{10} = 17.0 \text{ cents per gallon}$$

Such calculations may be made for a great variety of conditions, and values varying from a low of 12 cents per gallon to a high of around 35 cents per gallon for the alcohol can be calculated. That is, there is no single value for power alcohol in the competitive motor fuel market, but it is worth appreciably more than the gasoline it replaces, usually about 10 cents per gallon more. The Iowa State College bulletin (4) indicates that something like 18 cents per gallon, exclusive of taxes, is a fair value in Iowa. In Idaho, because of higher gasoline prices, the fair value following the same reasoning is about 23 cents per gallon, exclusive of taxes.

More than 1 million gallons of power alcohol were sold in the Midwest during the period 1936 to 1938. The sales price was 25 cents per gallon at the plant, exclusive of taxes. According to information from the manufacturers and distributors, this represented the top price at which it could find use, and required the distributors to charge a small premium for the blend. All agreed that 20 cents represents more nearly the competitive value in that area.

Power alcohol has to pay the same federal tax as gasoline, namely 1½ cents per gallon. In most states power alcohol pays the same state tax paid by gasoline. Idaho and Nebraska, however, specifically exempt power alcohol made from crops grown within continental United States from payment of the state tax. Some efforts have been made to secure exemption from payment of the federal tax on the alcohol and even on the alcohol-gasoline blend.

These tax differentials have a large bearing upon the value of farm products used for alcohol manufacture. Thus in Nebraska, assuming corn is the raw material and yields 2½ gallons of alcohol per bushel, the value of the tax differential calculated to a bushel of corn, becomes 12½ cents per bushel. In Idaho, assuming potatoes are used to make the alcohol and yield 22 gallons per ton, the value of the tax differential, calculated to a ton of potatoes, becomes $1.10 per ton.

The Production of Ethyl Alcohol

The methods used in the manufacture of power alcohol differ only in small detail from those used in the production of other grades, except that alcohol used to blend with gasoline must be practically moisture-free, which necessitates an additional processing step. The raw materials used for power alcohol manufacture need not be of as good quality as those used for beverage alcohol and various short cuts may be employed. But in general, the processes for the various kinds of alcohol have been the same and have not changed in many years. In fact, it has generally been considered the processes were not susceptible to fundamental improvement.

The raw materials used for alcohol manufacture are of two general types:

1. Those containing starch, such as the grains and white and sweet potatoes;
2. Those containing sugars, such as sugar beets and cane.

The processing of starch materials requires nine manufacturing steps:

1. Preparation of the raw materials for processing;
2. Sterilization of the mash and gelatinization of the starch by cooking with water;
3. Saccharification of the cooked starch to convert it to fermentable sugars;
4. Fermentation of the saccharified mash with carefully selected and prepared yeasts;
5. Distillation of the fermented mash to separate the crude alcohol;
6. Fractionation of the crude alcohol to prepare the grade required;
7. Denaturation of the alcohol to meet the requirements of the Federal Alcohol Tax Unit;
8. Evaporation of the spent mash to recover the valuable unfermented portion of the raw material;
9. Conversion of the carbon dioxide from the fermentation to liquid or solid form (dry ice).

The preparation of the raw materials varies with the material used. Grains are ground in a roll or hammer mill, with or without cleaning, to remove inert materials. Oats and rice must also be hulled for satisfactory plant operation. Potatoes and other tubers are usually washed but not ground. The amount of raw material storage required depends upon other storage facilities available on farms or in elevators near the plant.

In the usual procedure the ground grain is mixed with water to yield a mash containing about one part of total dry matter to six of water, and this mixture is cooked by direct steam injection in closed vessels provided with agitators. These cookers may be vertical or horizontal. Potatoes and sweet potatoes are generally cooked whole in a vertical cooker with a conical bottom to facilitate discharge, and are blown under pressure at the completion of the cooking period. The starchy materials must be cooked until the starch has gelatinized, which ordinarily requires 30 to 60 minutes at 5 to 40 pounds of steam pressure.

The cooked mash is then cooled, preferably by vacuum evaporation, to saccharification temperature, 55° to 65°C.; and at that point the saccharification agent is added. Ordinarily this is dried barley malt but rye malt is also used, and in European plants where the barley malt is made at the alcohol plant, green or undried malt is used. Malt is made by carefully steeping barley or other suitable grain until it is thoroughly moistened, then allowing it to germinate in piles on the malting floor or preferably in slowly rotating drums. When the diastatic value has reached a maximum, it is used as wet (green) malt or is dried for future use. The amount of dried malt used varies from around 8 per cent of the total grain to as much as 15 per cent. Potatoes require 15 per cent of dried malt on a dry basis. About 60 per cent as much green malt is required, on a dry basis, for grain or potatoes, as is needed of dried malt.

The saccharifying mash is held 60 to 120 minutes at the proper temperature, then cooled by pumping through a cooling coil to the fermenter. Preferably the fermenters are closed steel tanks provided with the necessary drain line, a cooling coil, and inlets for mash, inoculum, and water, and a carbon dioxide outlet. The yeast is prepared in special equipment provided for its cultivation, usually in the same kind of mash used in the fermenters. The inoculation ratio is preferably 5 to 10 per cent of the final mash volume. Fermentation is usually started with a mash temperature of about 25° C. and the maximum temperature is not permitted to rise above about 32° C. Fermentation requires from 48 to 96 hours, depending upon the kind of yeast, the mash concentration, the fermenting temperature, type of raw material, and other factors.

When the fermentation is complete, the fermented mash is pumped to the beer still where the crude alcohol is removed by direct or indirect steam heating. This crude alcohol vapor is then rectified by passing through another column from which it emerges at a strength of about 95 per cent alcohol by volume, ready for the final dehydration. The 5 per cent of water present in this alcohol may be removed by any of several methods, with lime or anhydrous calcium sulfate, by dehydration in vapor phase with any of several dehydrating agents, or by drying through reaction of the water with ethers. Ordinarily the method used is based upon the distillation with benzene.

Anhydrous alcohol is next denatured in accordance with Federal Alcohol Tax Unit requirements, under the supervision of government representatives stationed at the plant, and is ready for shipment.

The spent mash or stillage is taken to the feed recovery plant where the valuable protein, fats, minerals, and other constituents of feeding value are recovered. About one-half the total solids content can be recovered by screening, which is the first step used. Various processes have been developed for drying these solids, the most economical one using stack gases. The filtrate is evaporated to 25 to 35 per cent total solids content, mixed with the dried screenings, and this mixture again dried with steam or direct heat. Theoretically, all of the unfermented raw material should be recovered by this method.

The carbon dioxide formed during fermentation is collected and purified by washing, then compressed and cooled to a liquid, in which form it is sold in cylinders for carbonation of soft drinks and other uses. The liquid may be evaporated in suitable equipment to yield carbon dioxide snow which can be compressed into bricks known as dry ice. For every 46 pounds of ethyl alcohol there should also be formed 44 pounds of carbon dioxide. It usually is not economical to recover all of the carbon dioxide because the first evolved in the fermentation is contaminated with air. Usually 4.5 to 4.9 pounds of dry ice are made per gallon of alcohol produced.

The manufacture of alcohol from sugar-containing raw materials is simpler than from starchy raw materials. Molasses is simply diluted with water, with or without acidification with sulfuric acid, and is fermented. Ordinarily it is not economical to recover the unfermented solids. Sugar cane is crushed in the usual manner, and the liquor containing the sugar is fermented without further treatment. The bagasse remaining may be used in the manufacture of wallboard or used as fuel. Sugar beets and artichokes are washed, sliced, and placed in a diffusion battery. The diffusion liquor is fermented without further treatment. The pulp remaining is of value as a feed for cattle and sheep.

Equipment needed to carry out the process described has been quite well standardized, and while small improvements have from time to time been developed, the fundamental operations have remained unchanged for many years. The yields of alcohol and byproducts and the cost of factory operations generally are rather well known. The United States Department of Agriculture (2) has described the process and equipment in some detail. Reliable cost data have been given in this and other publications, and such estimates and statements are generally in good agreement if they are placed upon the same basis of raw material cost and quality, plant capacity, production, location, and byproduct credits.

A general cost estimate which may be regarded as approximately accurate for grains and tubers, is as follows, assuming a plant of economical size operating at capacity, costs being given in terms of a gallon of undenatured anhydrous ethyl alcohol:

Raw material at one cent per pound of dry matter content*	$0.26
Factory operations costs, including capital charges	0.08
Total charges	$0.34
Credit for byproduct feed at $25 per ton	$0.08
Credit for dry ice at $25 per ton, sales six months of the year	0.02
Total byproduct credits	$0.10
Net cost of alcohol with byproduct credits	$0.24

* Includes malt $1.00 per bushel (34 pounds).

Corrected to the same basis, the United States Department of Agriculture (2) estimate is $0.268 per gallon, the Iowa State College (4) estimate is $0.236 per gallon, and the Atchison Agrol Company (5) statement gives $0.228 per gallon as the cost.

Of the total cost, the charge for raw materials represents 79 per cent, and cost of factory operations only 21 per cent. Obviously, therefore, it is in the most economical possible utilization of the raw material through maintenance of the maximum possible yield, that large reductions in cost may be secured, and it should also be noted that dried barley malt costs three times as much per pound as does the principal raw material. Therefore, if it can be replaced by something cheaper, a gain can be made. Equally obvious is the fact that only minor gains can be made through reduction of factory operations charges.

How efficient is this orthodox procedure? The United States Department of Agriculture (2) reports that from potatoes containing 22.2 per cent dry matter this process yields 22.9 gallons of anhydrous alcohol and 76 pounds of dry residual solids per ton of potatoes. Since theretically 11.61 pounds of starch are required to produce one gallon (6.61 pounds) of alcohol, the alcohol represents 22.9 x 11.61 = 265.9 pounds of starch. Then the products, alcohol, carbon dioxide, and dry residual solids represent 76.0 + 265.9 = 341.9 pounds of dry matter per ton of potatoes charged to process. But a ton of potatoes of the quality assumed contains 2,000 x 0.229 = 458.0 pounds of dry matter. That is, there is a loss in process of 458.0 - 341.9 = 116.1 pounds of dry matter per ton of potatoes, or 25.4 per cent. In this case, the process is, therefore, only 74.6 per cent efficient.

When this method of analysis is applied to other published data, similar losses are found. Thus the Iowa State College bulletin (4) reports yield data with corn showing a 15.8 per cent loss in process, and yield data from commercial alcohol plants reveal losses varying from about 11 to 20 per cent of the dry materials charged to process. Similar losses in this process have been found in the experimental plant operations in Idaho, and have been confirmed in the laboratory.

This condition clearly indicates an opportunity for important reductions in alcohol costs, and two research objectives can, therefore, be set up:

1. Find a cheaper saccharification agent than dried barley malt;
2. Eliminate the cause of the large raw material losses occurring in the orthodox process for the production of ethyl alcohol.

These have been the objectives of the research program described in the following section.

Experimental Alcohol Plant Operations and Research

During the period of laboratory scale research at Moscow, prior to constructing the experimental plant at Idaho Falls, particular attention was given to the development of methods for the economical production of high quality green malt from locally grown barley. This program was successful and the green malt unit in the plant was quite satisfactory. In 1939 research was started on the development of a suitable commercial scale method and equipment for the production of mold bran, a still lower cost saccharification agent that had had thorough laboratory scale study at Iowa State College (4). This effort, too, was successful; and the plant was operated for several months using mold bran produced in a semi-commercial scale unit.

The mold bran was made by growing a selected strain of the fungus *Aspergillus oryzae* on treated wheat bran. Its chief advantage over green malt is the fact that it can be made in 2 days as compared with the 9 to 18 days required for green malt production. In addition somewhat less is required, so that it is a little more economical than is green malt. It is particularly well suited to use in large plant operations, and since it can be made at higher temperatures than can green malt, it is well adapted to use in areas where maintenance of satisfactory temperatures for malt production is somewhat difficult.

The development of two low-cost saccharification agents and of suitable methods and equipment for their production thus accomplished the first objective of the research program. The second problem, the low overall recovery, was not solved when the experimental plant was put into operation, and this was the principal objective of the research program during 1940.

It is not possible here to describe all of the research done. A very large number of yeast cultures was tested, cooking time and temperature were varied, several fermentation temperatures were used, many yeast nutrients and growth stimulants were studied at several concentrations, and much other work was done, all yielding nothing of importance as

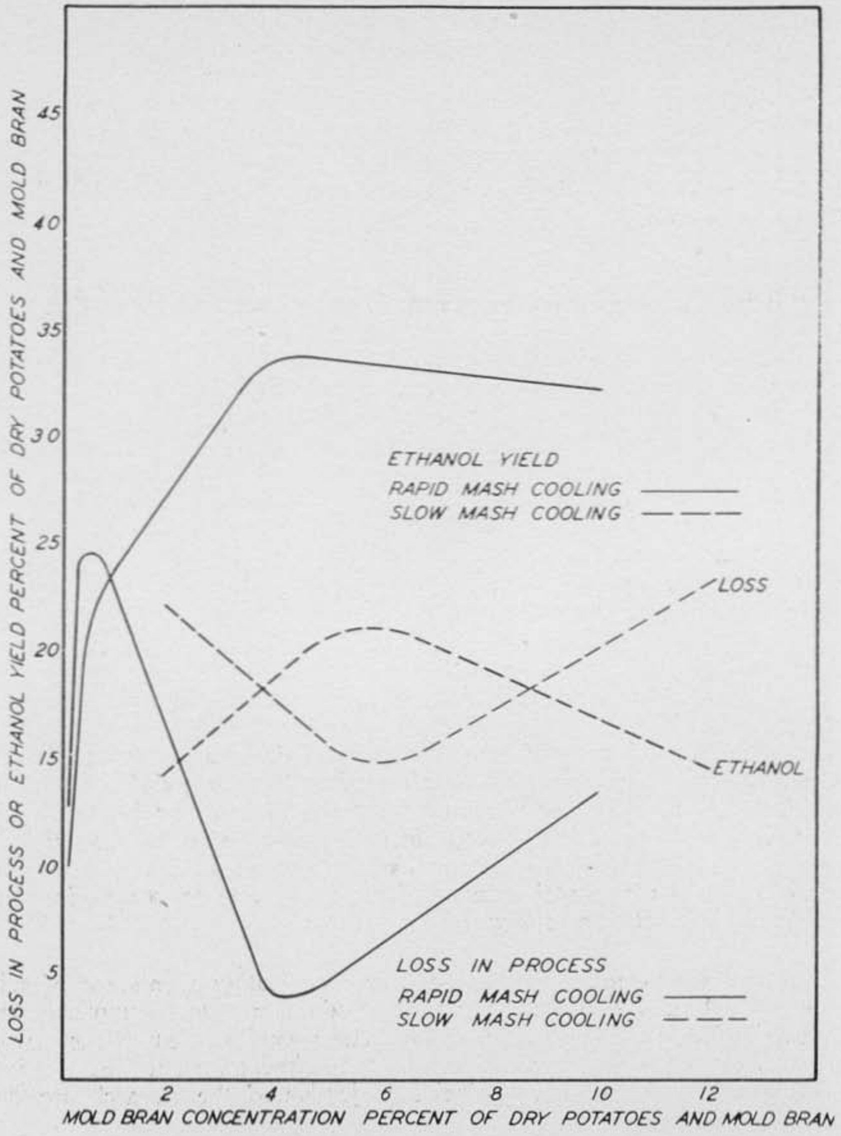

Figure 1. — Influence of the mold bran concentration upon the yields of alcohol and of residual solids from cull potatoes.

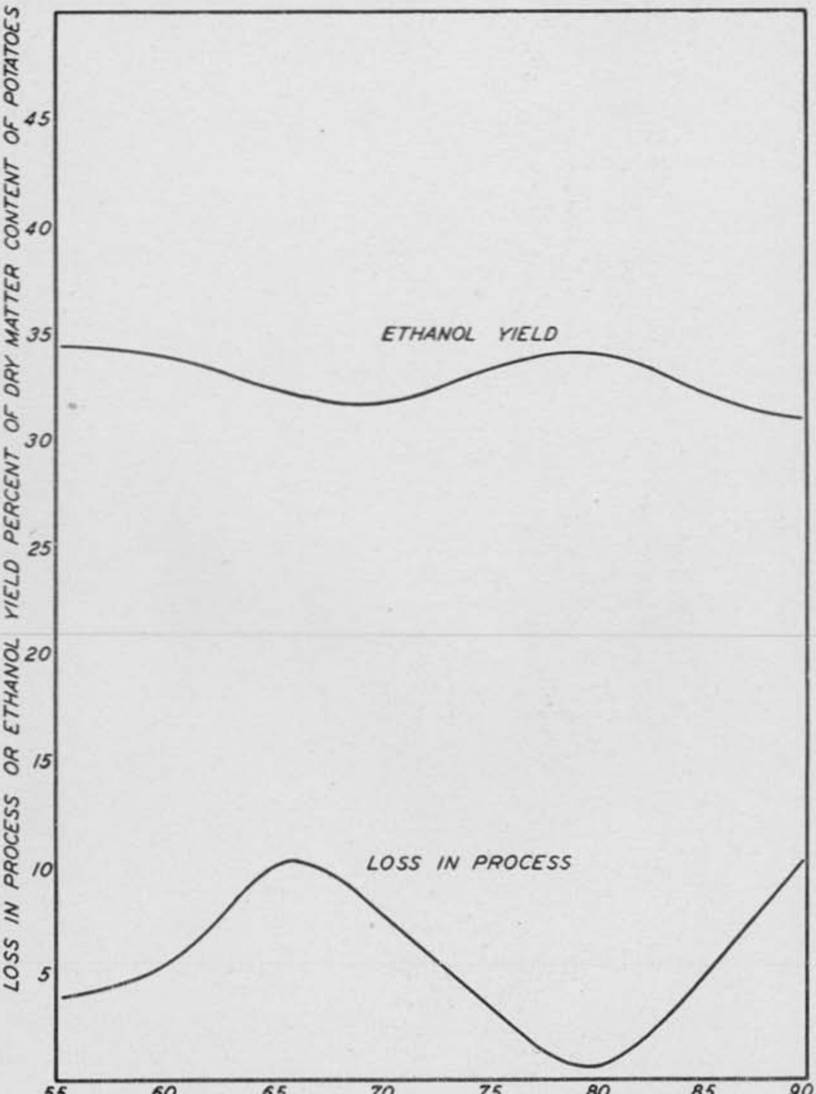

Figure 2. — Influence of the temperature in the first stage of two stage saccharification of potatoes.

regards improvement in overall recoveries. Overall efficiencies of around 80 per cent were the rule in the plant and in the laboratory scale fermentations. The laboratory scale fermentations with grains gave somewhat higher recoveries, usually around 85 per cent of theoretical.

Finally the answer was found in the laboratory during the summer of 1940. It was observed that when cooked starch mashes are cooled from cooking temperature (100° C. or above) to saccharification temperature (55° to 60° C.), some hitherto unsuspected irreversible physical-chemical changes occurred in the starch. These first were found through measurement of mash viscosities after saccharification, and they were immediately confirmed by fermentation studies. Subsequently X-ray diffraction studies at the Iowa Corn Research Institute gave further confirmation.

It then was found that if the cooked potatoes or grain mash were taken directly from the cooker, at a temperature of 100° C., and added immediately in a suitable mixer, with sufficient cold water containing the saccharification agent to lower the temperature instantaneously to 55° C., these irreversible changes could be almost entirely eliminated. With this rapid mash cooling procedure, it further was observed that the ratio of mold bran or malt to the potatoes or grain was a most important factor in determining the yields of alcohol and of residual solids.

This situation is described by the data shown graphically in Figure 1. Exactly the same relationships were found for other tubers and for all of the common grains, being somewhat less pronounced in the case of grains than with tubers. Furthermore, the optimum concentration of malt or mold bran with tubers was always almost exactly twice that for grains, all of which required the same amount of the saccharification agent. It will be noted that with both tubers and grains the amount of the saccharification agent for best yields is considerably less when the mash is quickly cooled than when the old slow cooling method is employed.

Table 1. — Comparison of alcohol and byproduct feed yields by old and new processes

	Old process			New process		
	Anhydrous alcohol per cent of total dry matter	Dry residual solids per cent total dry matter	Loss in process per cent of total dry matter	Anhydrous alcohol per cent of total dry matter	Dry residual solids per cent total dry matter	Loss in process per cent of total dry matter
Cull white potatoes	25.6	41.0	13.9	34.0	39.4	0.6
Average quality grain sorghums	30.5	29.8	16.5	33.8	38.4	2.0
High quality corn	34.2	28.0	11.8	37.6	32.4	1.3
Average quality corn	31.0	29.7	15.7	33.6	39.2	1.6
Low quality corn	29.6	32.0	15.9	31.9	40.4	3.4

Using this quick cooling and optimum concentration of saccharification agent, the yields shown in Table 1 were obtained. These are compared with the yields obtained from the same raw materials with slow mash cooling and larger requirements of the saccharification agent. Yields with mold bran and with green malt were practically identical when each was used at its optimum concentration.

This process could not, however, be applied in the Idaho Falls plant because of the limitations of the existing equipment and lack of funds for new. It was therefore necessary to modify the process to meet the needs imposed by this condition. It was found that if the cooked potato mash were quickly cooled by adding it to water — in a mixer and containing exactly one-fourth the total requirement of saccharification agent to reduce the temperature to 80° C. — the viscosity was reduced and the mash could be slowly cooled to 55° C., without the irreversible changes in the starch occurring. Then the balance of the saccharification agent could be added and this stage of the operation completed. With this method the experimental plant was able to get yields and efficiency fully as good as had been earlier realized in the laboratory. The influence of the temperature in the first stage of this two-stage operation is shown in Figure. 2.

Subsequently further improvements were developed in the laboratory but could not be used in the plant because of lack of required equipment. These improvements increased the yield of alcohol, with corresponding reduction in residual solids yield. Thus, from potatoes the alcohol yield was raised to 40.2 per cent of the total dry matter, while with high quality corn a yield of 41.5 per cent was realized, as compared with 34.0 and 37.6 per cent respectively by the original method. These modifications required removal of a large part of the potato skin or of the corn bran and oil, for which plant equipment was not at hand. Research on these and other modifications is continuing at Moscow.

Table 2. — Influence of the mold bran concentration upon the yield of ethanol from beet molasses

Mold bran Gm/100 gm. of molasses solids	Ethanol yield Gm/100 gm. of molasses solids	Gal/ton molasses
0	19.5	47.2
0.25	22.6	54.7
0.50	26.3	63.5
1.00	28.6	68.9
1.50	30.0	72.6
2.00	30.8	74.5
2.50	31.5	76.1
3.00	31.3	75.5
4.00	30.2	75.3
5.00	30.0	74.8

While the operations at Idaho Falls were particularly concerned with cull potatoes, attention was also given to the use of beet molasses and frozen wheat. This was desirable because such materials could be used during the approximately three months each year when cull potatoes are not available. Particularly interesting was the observation that the addition of small amounts of mold bran or malt to the fermentation of beet molasses greatly improved the alcohol yields. Whether this is due to action of the enzymes upon the carbohydrates of the molasses or to growth stimulants contained in the malt or mold bran is not known. In Table 2 is shown the influence of the mold bran concentration upon the yield of alcohol. It is interesting to note that the optimum concentration, in terms of ratio of mold bran to molasses solids, is the same as that for the grains.

The experimental plant at Idaho Falls represents an initial investment of $20,714.14. This does not include the expenditures for equipment revisions and improvements made in translating the new laboratory processes to plant scale. Complete records were made on more than 200 plant scale fermentations, which required a total of about 1,200 tons of cull potatoes during the two years of operation. Byproducts were not recovered except in small experimental lots. The principal markets for the alcohol were as an antifreeze, as a solvent for paints and lacquers, as a solvent for the dye used in the potato diversion program and for use in motor fuel. The sales price for the various grades varied from $0.325 to $0.400 per gallon at the plant, and the income from sales carried a large part of the operating expenses.

Byproducts

The production of ethyl alcohol from farm crops results in conversion of most of the starch or sugar content of such raw materials into ethyl alcohol and carbon dioxide in the ratio of 46 parts of the former to 44 parts of the latter. The other constituents of the raw material, plus the yeast generated in the process, remain in the spent mash. These proteins, minerals, fats, fiber, and other valuable feed materials can be economically recovered and used as supplements in rations for dairy and beef cattle, sheep, swine, and poultry. The carbon dioxide can readily be collected, compressed, and cooled to liquid form for use in the carbonation of beverages or to solid form (dry ice) for refrigeration.

Distillers' grains, in wet or dried form, have long been used in feeding programs. Corn distillers' dried grains find a ready market and are widely used in mixed feeds, especially for dairy cattle. Rye distillers' dried grains are also used but are generally regarded as of considerably less value. Dried grains from grain sorghums have also been commercially produced and marketed and are of a little higher quality than corn distillers' dried grains. The residue from potato alcohol manufacture has not previously been available for use in the United States, and consequently there is no background of experience with it, but it is very largely used in central European countries and apparently is regarded highly. From the standpoint of its chemical composition, it seems logical to believe it should be a desirable feed material.

Until recently these supplemental feeds were of interest chiefly because of their relatively high protein content, 25 to 35 per cent. Recently, however, attention has been directed toward other values, in particular the content of vitamins. Recently reported data show that corn distillers' dried grains from complete recovery plants (called dark distillers' grains or grains containing solubles) are a good source of riboflavin, thiamin, and of the chick dermatitis factor. Factor W is also present. Similar analyses of the residual solids from the fermentation of other farm crops have not yet been made, but work has been started at the Idaho Agricultural Experiment Station using potato, wheat, and barley residues.

The use of the new manufacturing process results in a change in feed composition, and there has not yet been opportunity to measure and evaluate such changes. Furthermore, the much larger feed recovery with the new process makes it desirable to obtain full information about this byproduct. Thus in the case of potatoes, the yield of byproduct feed in the new process is double that in the old method. The yields from grains are increased 15 to 30 per cent.

The Iowa State College bulletin (4) allows a credit of $25 per ton for this byproduct feed from corn. Quotations in the open market vary from $20 per ton to $35 per ton in bulk, depending upon the season, so that an average credit allowance of $25 per ton is conservative. But it must be kept in mind that only in the case of corn and rye distillers' dried grains is there an established cash market.

Preliminary analyses indicate that the residue from potato fermentations may have more value as a fertilizer than as a feed. Studies are now in progress to obtain quantitative data in this connection.

The United States Department of Agriculture (2) estimates the cost of producing dry ice at from $2 to $10 per ton. This wide variation is due primarily to variation in power costs, the major item in the production of dry ice. The Idaho bulletin (3) estimated the conversion cost at about $10 per ton.

The sales price of dry ice varies from about $25 per ton to $40 per ton, but small lots frequently sell at much higher prices. The markets are expanding, and it seems likely this trend will continue. Probably $25 per ton net at the plant represents a conservative basis for credit allowance.

The United States Department of Agriculture (2) allows a credit for fusel oil, and its recovery in the plant presents no unusual problems; but the amount produced and the trouble of collection and marketing hardly seem to justify its recovery.

It is interesting to note that the feed and dry ice byproducts find their best potential markets in agricultural areas. Thus alcohol manufacture is closely tied to farming for both raw material supply and byproduct and product utilization.

The Cost of Making Alcohol*

In this section an effort is made to supply information on the important question of the cost of making alcohol. Of course, there is no such thing as "the" cost of producing alcohol, any more than there is "the" cost of raising a sack of potatoes. Costs will vary from one plant to another because of differences in the cost of fuel, in labor costs, and

Table 3. — Alcohol plant operations cost per gallon of undenatured anhydrous alcohol

	Idaho Falls Plant at 500 gallons daily	2,500 gallon per day plant at capacity	10,000 gallon per day plant at capacity
Fuel, power, and water	$0.0372	$0.0160	$0.0200
Personnel	.0800	.0350	.0229
Maintenance	.0121	.0094	.0031
Taxes, bonds, and insurance	.0131	.0086	.0042
Depreciation at 10% per year	.0242	.0189	.0157
Interest at 5% per year	.0121	.0094	.0079
Total	$0.1787	$0.0973	$0.0738

Table 4. — Raw material charges per gallon of undenatured anhydrous ethyl alcohol

	Corn or grain sorghum 97% Wheat bran 3%	Barley or wheat 97% Wheat bran 3%	White potatoes 94% Wheat bran 6%
Alcohol yield lbs. per 100 lbs.	33.60	29.60	34.00
gallons per 100 lbs.	5.05	4.58	5.14
Raw material cost per gal. alcohol			
Raw material at $0.70 per 100 pounds dry basis	$0.1386	$0.1528	$0.1362
0.80	.1584	.1747	.1556
0.90	.1782	.1965	.1751
1.00	.1980	.2183	.1946
1.10	.2178	.2402	.2140

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* In the preparation of this section of the report, the authors gratefully acknowledge the assistance of Mr. Kenneth Dick, Certified Public Accountant and Assistant Bursar, University of Idaho.

other items of plant operations charges. The price and quality of raw material will vary, and byproduct credits will not be the same at all points. But a representative cost statement can be offered, and with proper interpretation it will serve to indicate the probable cost of producing alcohol in any particular area, or more exactly, it will indicate the cost that can be attained under a particular combination of conditions.

It is convenient to analyze costs in three steps: (1) factory operation charges; (2) raw material charges; and (3) byproduct credits. Such an analysis neglects sales costs, and no effort is made in this report to consider them. The Iowa State College bulletin (4) has already given an adequate treatment of this aspect of the general economic situation. This report does not attempt to give a cost figure for denaturation because federal requirements in this connection change from time to time.

Because of the combination of production and research at Idaho Falls, actual plant operation charges have not been used in this report as such, but as a basis for the computation of alcohol production costs for a plant capacity of 500 gallons per day. In making the estimates for the expanded production of the Idaho Falls plant, steam consumption per gallon, yield of alcohol per ton of potatoes, and labor distribution obtained in connection with the experimental plant operations were used as a basis for the computations. The estimate of factory operations charges presented for 2,500 gallons per day and 10,000 gallons per day production are taken from the Iowa State College bulletin (4).

Table 5. — Byproduct credits per gallon of undenatured anhydrous ethyl alcohol

	Corn or grain sorghum 97% Wheat bran 3%	Barley or wheat 97% Wheat bran 3%	White potatoes 94% Wheat bran 6%
Byproduct feed yield			
pounds per 100 pounds	38.40	44.80	39.40
pounds per gallon alcohol	7.60	9.78	7.67
Credit with sales at $20.00 per ton dry basis	$0.0760	$0.0978	$0.0767
22.50	.0855	.1100	.0863
25.00	.0950	.1222	.0957
27.50	.1045	.1345	.1055
30.00	.1140	.1467	.1150
Dry ice credit, with sales at $25.00 per ton*	$0.0200	$0.0200	$0.0200
Dry ice credit, with sales at $32.50 per ton*	$0.0300	$0.0300	$0.0300

* Assuming cost of production $10.00 per ton and sale of output during half the year.

The cost of an erected alcohol plant is influenced by many factors, but in general the cost varies from $50 per gallon of daily capacity for a 10,000 gallon per day plant to $100 per gallon of daily capacity for a 500 gallon per day plant.

The charge for raw materials depends upon their unit cost and the yields of products and byproducts from them. To avoid confusion and possible misunderstanding, yields and costs in this report are based upon moisture-free raw materials, and the wheat bran used to prepare the saccharifying agent is included as one of the raw materials. That is, yields and costs are based upon the dry matter content of the total raw material brought into the plant. Knowing the moisture content of a particular grain or tuber, it is then a simple matter to translate the data of this report to that raw material, or mixture of raw materials. This is illustrated in the examples following the tables. Three cost statements are given. The first applies to corn or grain sorghums of average quality, the second applies to barley or wheat, and the third to cull white potatoes.

The cost of plant operations will vary a little from one raw material to another, but so little that it is not necessary to make such correction. The plant operations charges of Table 3 can safely be applied to the utilization of any of the three raw material types selected, assuming sound plant design, location and operation.

In Table 4 are shown the raw materials charges. In preparing this table, it was assumed that wheat bran can be had at the same price as the grain or tuber, on a dry matter content basis. If that is not the case, then the price given is the mean price of the indicated mixture.

In Table 5 are given the byproduct credits. Byproduct feed prices are given on a dry matter content basis. Since the feed as marketed usually contains about 8 per cent of moisture, the price on the dry basis multiplied by 0.92 is equivalent to the price on the basis of the normal moisture content. For example, if the sales price on an 8 per cent moisture basis is $25 per ton, this is equivalent to $\frac{\$25.00}{0.92} = \$27.17$ per ton dry basis.

Two possible dry ice credit values are given, one based upon sale of the plant output during half the year at $25 per ton, the second on the basis of sale of the plant output during half the year at $32 per ton. In both cases, a cost of production and packaging of $10 per ton is assumed. As noted previously, some manufacturers estimate the cost of manufacture (probably not including packaging) at as low as $2 per ton.

With the data of Tables 3, 4, and 5, the cost of alcohol made under a wide variety of conditions can readily be calculated. Assume, for example, that cull white potatoes containing 21.5 per cent dry matter (78.5 per cent moisture) cost $3 per ton and are processed in a plant of 500 gallon per day capacity, operated at full capacity, with a byproduct feed credit at $27.50 per ton, and that the carbon dioxide is wasted. The raw material cost is $\dfrac{\$3.00}{2{,}000 \text{ x } 0.215 \text{ x } 100} = \$0.70$ per 100 pounds of dry matter.

The cost of the undenatured anhydrous alcohol, therefore, is $0.1787 + $0.1362 - $0.1055 = $0.2094 per gallon. If the potatoes are processed in a 2,500 gallon per day plant with the same feed credit and with a dry ice credit of $0.0200 per gallon of alcohol, the cost of the undenatured anhydrous alcohol is $0.0973 + $0.1362 - $0.1055 - $0.0200 = $0.1080 per gallon.

As another example, assume that grain sorghum costs $0.80 per 100 pounds and contains 84.2 per cent of dry matter (15.8 per cent moisture) and is processed in a 10,000 gallon per day plant. Assume, further, that the byproduct feed is credited at $30 per ton and dry ice brings $25 per ton. The cost of the dry raw material is $\dfrac{\$0.80}{100\ (0.842)} = \$0.95$ per 100 pounds of dry matter. The cost of the undenatured anhydrous alcohol is $0.0738 + $0.1881 - $0.1140 - $0.0200 = $0.1279 per gallon. If, however, the feed brings only $25 per ton, dry basis, the cost of the alcohol is $0.0738 + $0.1881 - $0.0950 - $0.0200 = $0.1469 per gallon.

These calculations are all made on the basis of capacity operation during 330 days per year. Since taxes, bonds, insurance, depreciation, interest, and a part of maintenance and personnel charges are fixed, it is obvious that with less than capacity operation, the alcohol cost will be increased. At half capacity, for example, the increase will be approximately $0.0350 per gallon in the 10,000 gallon plant, $0.0500 in the 2,500 gallon plant, and $0.0650 in the 500 gallon per day plant, as compared with capacity operation.

The cost of alcohol made with the new mashing and saccharification process is $0.08 to $0.10 per gallon lower than that made by the present orthodox process, as shown by a comparison of the above cost calculations with those given earlier in this report. This is due to the elimination of expensive dried barley malt and improvement in alcohol and byproduct yields.

The above cost statements do not give effect to the economies inherent in coupling alcohol production with the manufacture of starch, beet sugar, stock feed, or food products. In this type of operation, the alcohol production serves as a means for profitable utilization of carbohydrate wastes, and thus may be made at somewhat lower cost than in a plant designed and operated to produce alcohol alone. In addition, further savings may result in such instances from a better division of fixed costs.

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