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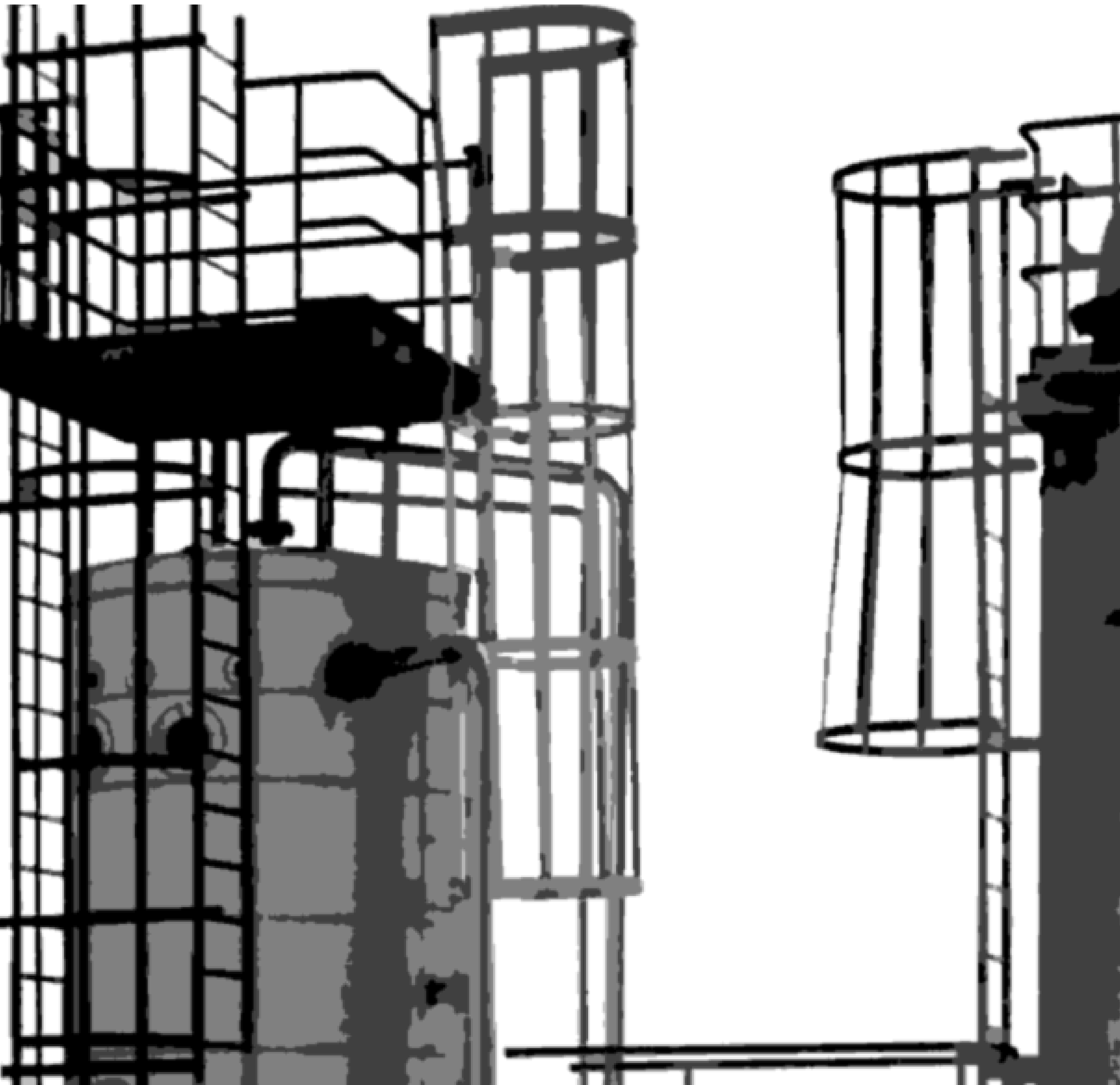
Whey to Ethanol: A Biofuel Role for Dairy Cooperatives?



Abstract

Pertinent information regarding whey-to-fuel ethanol production is explored and reviewed. A potential of producing up to 203 million gallons of fuel ethanol from whey in 2006 was estimated, and dairy cooperatives could have a share of 65 million gallons. Two whey-ethanol plants are currently operated by dairy cooperatives, producing a total of 8 million gallons a year. Successful operations of the plants since the 1980s indicate that (1) fuel ethanol production from whey is technically feasible, (2) whey-to-fuel ethanol production technologies and processes are mature and capable of being adopted for commercial operations, and (3) producing fuel ethanol from whey is economically feasible. However, in this era of whey products' price uncertainties, a key consideration in assessing the feasibility of a new whey-ethanol venture should be the valuation of the opportunity cost of whey as feedstock for fermentation. A new whey-ethanol plant probably should have an annual production capacity of at least 5 million gallons of ethanol. Some historical lessons on the pitfalls to avoid are summarized.

Key Words: Whey, whey permeate, permeate mother liquor, lactose, ethanol, dairy cooperatives.

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Cover illustration from photograph of Dairy Farmers of America’s whey-to-ethanol plant in Corona, California, courtesy Dairy Farmers of America.

Preface

In this era of looking for alternative energy sources, the idea of fermenting lactose in surplus whey (which traditionally has been regarded as a waste product) to produce fuel ethanol has gained attention. This study sets out to explore issues that are pertinent to understanding the viability of producing fuel ethanol from whey:

- The volume of lactose in whey that is available for fermentation and the potential volume of fuel ethanol production.
- The current status of whey-to-fuel ethanol production.
- The technologies and processes of producing fuel ethanol from whey.
- The costs and returns of producing fuel ethanol from whey.
- The organization of the whey-ethanol enterprise and the role dairy cooperatives may play.

Acknowledgements

The author would like to thank Mr. John Desmond of the Carbery Group and Dr. M. Clark Dale of Bio-Process Innovation, Inc., for providing information on the whey-ethanol production processes. For their cooperation in sharing information about whey-ethanol plant operations, the Dairy Farmers of America and Land O'Lakes are also gratefully acknowledged. Credits are also due to many people who were consulted during the course of this study.

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Highlights

An estimated 90.5 billion pounds of whey was generated as a byproduct of cheese production in 2006. Besides the liquid carrier, the composition of whey is approximately 0.3 percent butterfat, 0.8 percent whey proteins, 4.9 percent lactose, and 0.5 percent minerals. Cumulatively, there were 4.4 billion pounds of lactose contained in the whey produced that year.

Whey may be made into many products with various processes and technologies. Condensed whey, dry whey, dry modified whey, whey protein concentrate and isolates, as well as lactose (crystallized and dried) are the often cited whey products. There are many other secondary and tertiary products that can be derived from whey, but the volume of whey used in these products is relatively small.

Whey products produced in 2006 contained an estimated total of 1.9 billion pounds of lactose. Therefore, about 2.5 billion pounds of surplus lactose were unaccounted for by whey products. This vast amount of surplus lactose could be fermented to produce an estimated 203 million gallons of ethanol, assuming complete consumption of lactose in fermentation and ethanol conversion efficiency at 100 percent of the theoretical yield. Dairy cooperatives' share of the whey-ethanol potential could be 65 million gallons.

There are two industrial-scale whey-ethanol plants in the United States, at Corona, Calif., and Melrose, Minn. Both began operation in the 1980s and are currently owned and operated by dairy cooperatives. Together they produce 8 million gallons of fuel ethanol a year.

The whey-to-ethanol plant commissioned in 1978 by Carbery Milk Products Ltd. of Ireland is believed to be the first modern commercial operation to produce potable (drinkable) alcohol. Starting in 1985, it has produced fuel ethanol as well. The Carbery process developed by the company has been adopted by plants in New Zealand and the United States. New Zealand started using fuel ethanol produced from whey in August 2007.

All ethanol production processes share some basic principles and steps. Whey permeate from protein ultrafiltration is concentrated by reverse osmosis to attain high lactose content. Lactose is fermented with some special strains of yeast. Once the fermentation is completed, the liquid (beer) is separated and moved to the distillation process to extract ethanol. This ethanol is then sent through the rectifier for dehydration and then denatured. The effluent (stillage and spent yeast) may be discharged to a treatment system, digested for methane gas, sold as feed, or further processed into food, feed or other products.

To be economically viable, a dehydration plant (and by inference, an ethanol plant) needed to have a minimum daily capacity of 60,000 liters of ethanol (about 15,850 gallons a day or five million gallons a year), according to a 2005 New Zealand report. The estimated “at-gate” cost (operating and capital service costs) of producing ethanol from whey permeate at maximum technical potential, with a level of uncertainty of +/- 20 percent, was N.Z. $0.6-0.7 per liter. Using a currency exchange rate of N.Z. $1 = U.S. $0.7, the estimated cost translated to U.S. $1.60-1.85 per gallon. This estimate is similar to the costs quoted by sources in the United States: about $1 per gallon of operating cost and a capital service cost that is predicated on the capital cost ranging from $1.50 to $4 per annual gallon for a commercial operation, depending on the scale of the plant. The estimated operating cost assumes that whey permeate used in ethanol fermentation is a free (no cost) feedstock. Capital cost is the cost of the plant construction project.

There is an opportunity cost of lactose for ethanol fermentation only if there are competing uses of the same lactose, such as manufacturing dry whey, lactose, or other whey products. If there is no such competition, then the whey permeate somehow has to be disposed of and the opportunity cost of lactose for ethanol fermentation is likely to be zero or even negative.

It takes 12.29 pounds of lactose to produce a gallon of ethanol, if the lactose is completely consumed in fermentation and ethanol conversion efficiency is 100 percent of the theoretical yield. For every $0.01 net lactose value (price of lactose net of processor's cost), the feedstock cost for fermentation would be $0.1229 per gallon of ethanol. If lactose consumption is less than complete in fermentation and ethanol conversion efficiency is less than 100 percent of the theoretical yield, then more than 12.29 pounds of lactose is required to produce a gallon of ethanol and the feedstock cost would be higher.

Whether it is economically feasible to produce ethanol from whey permeate is determined by the balance of the production costs and the expected revenues. Net returns from the ethanol enterprise should be measured against the profitability of making other whey products or of other uses, to determine whether ethanol production is a more worthwhile undertaking. A further consideration should be which of the whey enterprises fit best with a cooperative's overall business strategy.

The fact that the two whey-ethanol plants have been in operation for more than 20 years is an indication that (1) fuel ethanol production from whey is technically feasible, (2) whey-to-fuel ethanol production technologies and processes are mature and capable of being adopted for commercial operations, and (3) producing fuel ethanol from whey is economically feasible.

In assessing the feasibility of a new whey-ethanol plant, the cost of whey permeate as feedstock needs to be carefully evaluated in this era of whey products' price uncertainties. Other important factors to consider besides the feedstock cost are (1) an appropriate plant scale that would minimize capital cost and the cost of assembling feedstock, (2) an appropriate technology and processes that would minimize operating cost, (3) best alternatives for using and/or disposing of the effluent, (4) ethanol price, and (5) various government production incentives.

Dairy cooperatives are certainly well-positioned to coordinate whey assembly for ethanol production. However, in view of the current high and unsettled dry whey products prices, there are great uncertainties concerning the long-term development of the whey-ethanol production enterprise.

There was a very high attrition rate of fuel ethanol plants during the decade of 1980s. Experiences of that period provide some lessons that may be relevant to future commercial whey-ethanol development. To be successful, a fuel ethanol plant should have proper technology selection, proper engineering design, adequate research support, credible feasibility studies, adequate financing; and personnel with technical and managerial expertise in the biochemical process.

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Introduction

A total of 90.5 billion pounds of whey was estimated to have been generated as a byproduct of cheese production in 2006, comprising about 85.8 billion pounds of sweet whey and 4.7 billion pounds of acid whey (Table 1, *next page*). A general rule of thumb is that the volume of sweet whey is about nine times the volume of cheese produced and the acid whey volume is about six times that of cottage cheese. Over the last 5 years, from 2001 to 2006, the volume of whey increased by 15 percent, commensurate with the increases in the production of cheeses.

The composition of whey varies with the components in milk that is used for making cheese, the variety of cheese made, and the cheese-making process employed. Whey contains approximately 0.3 percent butterfat, 0.8 percent whey proteins, 4.9 percent lactose, and 0.5 percent minerals (*Wisconsin Center for Dairy Research*).

Butterfat is traditionally of high value, and most plants separate it for use as an ingredient for further processing. The remaining whey may be made into various products by using an array of processes and technologies, or is otherwise disposed of (Table 1 and Figure 1, *page 3*).

Whey can be condensed or concentrated, dried, fermented, delactosed, demineralized, and deproteinated. It is adaptable to ultrafiltration, reverse osmosis, ion exchange, electrodialysis, and nanofiltration (*Kosikowski, et al*).

The main whey products are dry products: dry whey, lactose, and whey protein concentrate (Table 1 and Figure 1). These whey products are storable for later distribution over a wide area, even internationally. Condensed whey also uses a significant amount of whey, but the market is limited due to its wet form.

There are many other secondary and tertiary products that can be derived from whey (*Kosikowski, et al*). However, the volume of whey used in these products is relatively small (*Yang, et al*).

While whey products have found wider uses in recent years and of late have become valuable commodities (table 2 and sidebar, page 4), making these products was originally considered a lower-cost, last-resort alternative to dumping surplus whey.

Most of the components of whey can quickly deplete oxygen levels in natural water systems (*Hamilton*). The biochemical oxygen demand (BOD) of whey is about 3.5 pounds per 100 pounds of whey or 35,000 ppm, and its chemical oxygen demand (COD) is about 68,000 ppm (*Webb, et al*). Such high levels of pollutants make disposing of whey problematic.

Methods of disposing of surplus whey include animal feeding, land spreading, or discharging it after treatment for BOD reduction. There are also some recent cases of feeding whey to anaerobic digesters to produce methane gas (*Dairy Facts*).

Animal feeding and land spreading have limitations (*Cotanch, et al; Wendoff; Kosikowski, et al*). Continuous land disposal of cheese whey can endanger the physical and chemical structure of the soil, decrease the crop yield, and lead to serious water pollution problems (*Belem, et al*).

Treating whey for BOD reduction before discharging it is costly. As an exercise to evaluate the cost, cursory searches on the Internet selected 20 sewage districts in as many States (not a random sample) that posted clearly discernible sewage rates on volume, BOD, etc., for 2006-07. Average volume charge was $2.50 per 1,000 gallons of sewage (3 cents

Table 1—Fluid whey, and whey and modified-whey products produced, 2001-2006, United States

	2001	2002	2003	2004	2005	2006
Estimated fluid whey volume[1]:			*-----Billion pounds-----*			
Sweet type	74.3	76.9	77.0	79.9	82.3	85.8
Acid type	4.5	4.5	4.6	4.7	4.7	4.7
Total	78.8	81.4	81.6	84.6	87.0	90.5
Whey and modified-whey products:			*-----1,000 pounds-----*			
Condensed whey, solids, sweet type, human	81,484	108,250	114,656	91,227	79,247	106,919
Dry whey	1,045,655	1,115,321	1,085,165	1,034,898	1,040,692	1,100,346
Reduced lactose and minerals	129,245	124,670	84,110	84,893	98,371	91,596
Lactose	519,161	563,110	613,976	665,621	713,975	738,656
Whey protein concentrate	336,221	313,239	357,944	355,854	383,926	427,724
Whey protein isolates[2]			22,333	27,677	27,595	30,673
Whey solids in wet blends, animal[3]	39,851	37,656				

[1] Estimated at 9 times cheese production for sweet whey and 6 times cottage cheese for acid whey.
[2] New data series started with the year 2003. (*Dairy Products*, October 4, 2005).
[3] Not shown when fewer than three reported or individual plant operations could be disclosed.
Sources: *Dairy Products*, *Annual Summary*, USDA National Agricultural Statistics Service, selected years, unless otherwise specified.

per hundredweight) discharged, and average BOD surcharge was $0.27 per pound of BOD that was above a basic level, usually 200-300 ppm. In addition, some jurisdictions also had surcharges on COD and other pollutants.

These various charges highlight the high cost of surplus whey disposal. Making whey products reduces the surplus whey volume, saves on the cost of disposing of whey, and has the prospect of breaking even or making profit in whey plant operations. Thus, it is important for the industry to find new ways to use more whey.

Advances in membrane and filtration technology since the late 1970s enable processors to “harvest” whey proteins, which are of high nutritional value. In recent years, whey proteins have become popular for use in fortifying more and more foods, beverages, infant formulas, and nutraceuticals. The growth in demand has pushed up whey protein concentrate production by 20 percent in 3 years since 2003 and whey protein isolates by 37 percent (Table 1).

Harvesting whey proteins still poses the problem of dealing with whey permeate, which retains most of the lactose and other solids. Whey permeate may be dried for feed or food uses, but the largest volume is used to produce lactose. However, lactose has somewhat limited application in food products because of its low digestibility and poor solubility: it is prone to crystallization (*Audic, et al; Alexander, et al*). In addition, producing lactose has a leftover product—permeate mother liquor, which contains about 60 percent lactose (dry basis)—that still needs to be disposed of (*Dale, et al*).

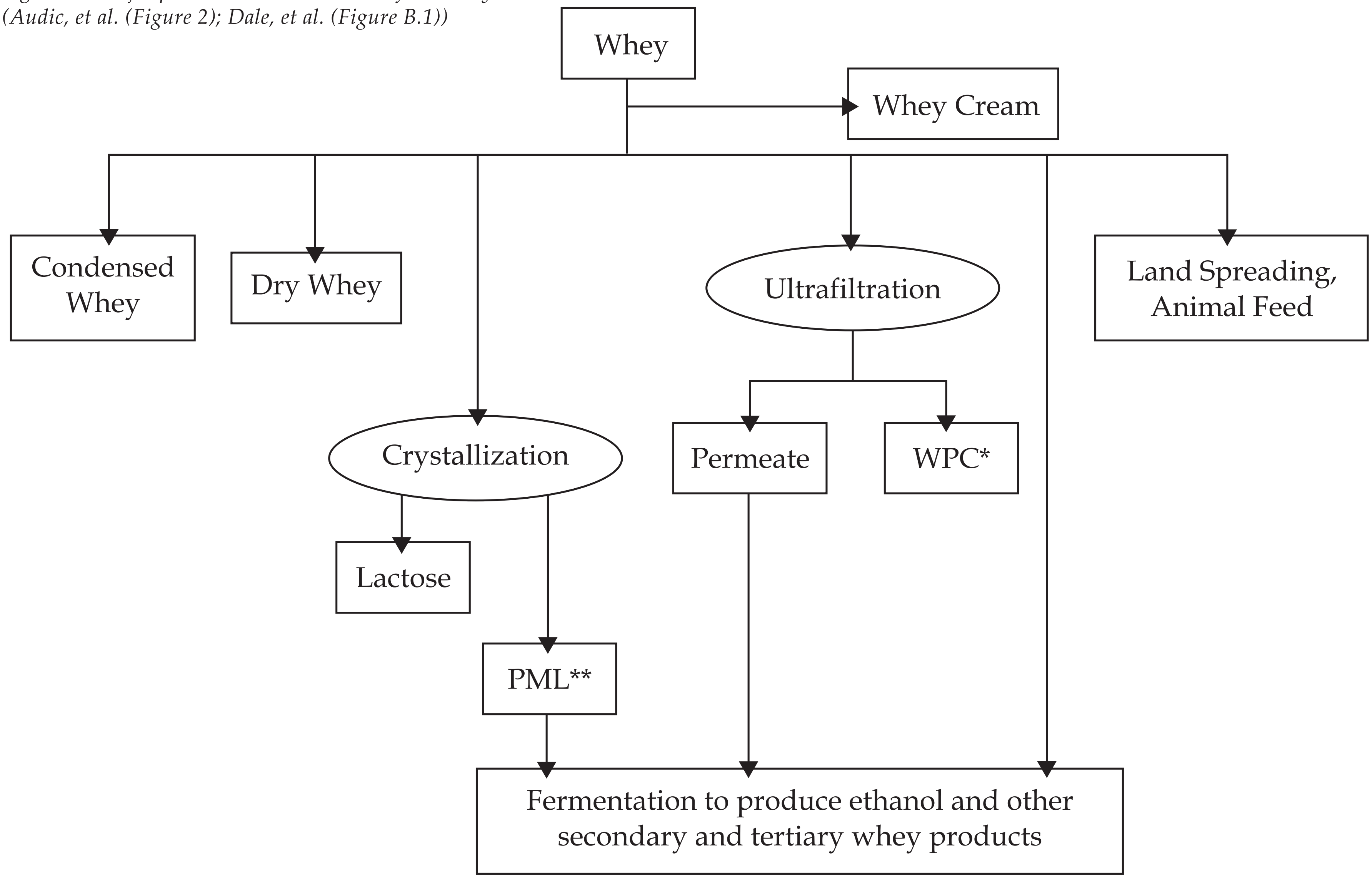
The issue of profitably handling the large volume of surplus whey remains. Producing ethanol by fermenting lactose contained in whey, whey permeate, and permeate mother liquor may be a promising alternative. In common usage, ethanol is often referred to simply as alcohol.

The best known, first commercially operated whey-to-ethanol plant was commissioned in April 1978 by Carbery Milk Products Ltd. of Ireland to produce potable (drinkable) alcohol (*Sandbach*). Since 2005, the company has been suppling ethanol made from whey to an oil firm for E85 and E5 blends (*The Maxol Group; Irish Examiner.com*).

The Carbery process has been adopted by plants in New Zealand and the United States.

Internationally, the most notable whey-to-ethanol producer is Anchor Ethanol Ltd, which is wholly owned by the New Zealand dairy cooperative Fonterra. It operates three ethanol plants with an annual total production of about 5 million gallons, and claims to be the largest ethanol producer in the world that uses whey (from casein plants in this case) as feedstock. The ethanol has been used for food, beverage and industrial applications (*Anchor Ethanol; Mackle*). Beginning on August 1, 2007, the company's fuel

Figure 1-- Major products and uses derived from whey (Audic, et al. (Figure 2); Dale, et al. (Figure B.1))



*WPC: Whey protein concentrate

** PML: Permeate mother liquor, which contains 60% lactose, dry basis

Table 2—Average annual prices of whey products, carlot or trucklot quantities in bulk packages, 2001-2006, and monthly prices since 2006

Year	Whey powder, edible nonhygroscopic (Central)	Lactose, edible (Central & West)	Whey protein concentrate, edible 34% protein (Central & West)
		-----Dollars per pound-----	
2001	0.2777	0.2090	0.7777
2002	0.1971	0.2042	0.5205
2003	0.1684	0.2094	0.4968
2004	0.2395	0.2262	0.5869
2005	0.2781	0.2012	0.8430
2006	0.3425	0.3333	0.6981
Month			
2006			
January	0.3482	0.2427	0.8004
February	0.3529	0.2492	0.7524
March	0.3193	0.2500	0.6825
April	0.2875	0.2678	0.6144
May	0.2789	0.2816	0.5990
June	0.2811	0.2873	0.5800
July	0.2901	0.3328	0.5935
August	0.3171	0.3438	0.6209
September	0.3599	0.3628	0.6703
October	0.4058	0.4139	0.7468
November	0.4308	0.4392	0.8295
December	0.4388	0.5288	0.8869
2007			
January	0.5096	0.5430	1.0012
February	0.6788	0.6062	1.1784
March	0.7768	0.6681	1.3506
April	0.7807	0.9227	1.4801
May	0.7376	0.9370	1.5500
June	0.7385	0.9273	1.6210
July	0.6743	1.0353	1.6460

Source: *Dairy Market News*, USDA Agricultural Marketing Service.

High prices for dry dairy products due to diverse reasons

Recent high prices of dry dairy products are due to the following factors *(USDA Economic Research Service; OECD-FAO)*:

- European Union (EU) agricultural reforms in 2003 reduced the incentives for producing butter and dry nonfat milk, thus shifting more milk solids into cheese.
- Worldwide growth in both cheese consumption and an array of milk protein concentrates (MPC) also reduces the amount of milk protein that might otherwise be made into nonfat dry milk.
- Weather-related problems in Australia reduce the amount of dry dairy products available for export.
- A strong world economy spurs growth in world demand for dairy products.
- Lower exchange rates of U.S. dollar in recent years improve the competitiveness of U.S. dairy products.

Policy changes in the EU and worldwide growth in cheese and MPC demand represent fundamental changes, while weather problems, economic growth, and exchange rates are to some extent cyclical.

Dairy Farmers of America's ethanol-from-whey plant in Corona, California. (Photograph courtesy of Dairy Farmers of America)

ethanol has become available (*Farmnews for NZ Farmers*). It has been blended with gasoline and sold commercially as E10.

In the United States, there are two industrial-scale plants that produce fuel ethanol from whey. Both are currently owned and operated by dairy cooperatives. Dairy Farmers of America (DFA) operates the Corona, Calif., plant through its Golden Cheese Company subsidiary. The Melrose, Minn., plant operated by Land O'Lakes is part of a cheese production joint venture between Land O'Lakes and DFA.

The Corona plant has been in operation since 1985, except for a hiatus of more than a year from 1998 to 2000. It is located on the same premises as the cheese plant. The ethanol plant was originally licensed to use the Carbery process for producing ethanol from whey permeate. It has a production capacity of 5 million gallons of ethanol per year. Proprietary yeast is propagated at the plant, and the cells are recycled and reused several times. Fermentation takes place in eight batches, and each batch requires slightly more than 24 hours to complete. In the distillation column the ethanol is concentrated to 190 proof. It is then dehydrated to 200 proof for fuel ethanol and is denatured before shipping.

(DFA recently announced the closure of the Corona facility. The plant would operate at a reduced capacity beginning August 31 and cease production of American block cheese and whey products by December 31, 2007 (*DFA*).)

The Melrose plant began operation in 1982 and currently is producing about 3 million gallons a year. It is located a couple hundred feet away from the cheese plant. All products and utilities are brought to the ethanol plant via a pipe rack from the cheese plant. The technology was originally developed by Kraft, and yeast propagation is also proprietary. It uses a fed-batch fermentation system that ferments seven batches a day. Whey permeate is sent to fermentation tanks and inoculated with yeast. After fermentation, water and ethanol are separated from the lactose distillers solids using an old whey evaporator. The water and ethanol mixture is then sent to a distillation column and a molecular sieve for concentration and dehydration. (Note: In a fed-batch system, substrate is fed into the fermentation tank at constant intervals, while effluent is removed continuously (*Roehr*).)

Both plants concentrate lactose in the whey permeate to more than double its natural strength before fermentation. No other pretreatment on the feedstock is required. Lactose is almost completely consumed in the fermentation process. The resulting beer contains a level of ethanol that is required for efficient distillation and dehydration. Most effluent from ethanol production is sold for animal feed.

The ethanol production of 8 million gallons from these two plants accounts for a minor portion (less than 1 percent) of total U.S. annual fuel ethanol production. The total surplus lactose volume as calculated below shows that potential exists to produce up to 203 million gallons of ethanol a year from whey. This study attempted to ascertain the feasibility of expand-

Table 3—Estimated volume of lactose in whey products, 2006

Item	Product	Lactose	
	Million lbs	*Percent*[1]	*Million lbs*
Lactose in sweet whey	85,809.0	4.9	4,205
Lactose in cottage cheese (acid) whey[2]	4,651.9	4.9	228
Total lactose volume (estimated)			4,433
Lactose used in whey products (estimated):			
Condensed whey, solids content[3]	106.9	77.5	83
Dry whey products			
Dry whey, Total	1,100.3	74.4	819
Reduced lactose & minerals[4]	91.6	71.3	65
WPC, 25.0-49.9% protein[5]	297.5	51.0	152
WPC, 50.0-89.9% protein[6]	130.3	5.0	7
Whey protein isolates, 90.0% and higher	30.7	1.0	0
Lactose[7]	738.7	99.0	731
Total lactose used in whey products			1,857
Lactose unaccounted for by whey products			2,576

[1] Adopted from *Wisconsin Center for Dairy Research*, unless otherwise specified.
[2] Cottage cheese whey contains 4.9% lactose (*Kosikowski, et al*, p. 427). Other references tend to report lower lactose content.
[3] Percentages among solids in dry whey, not counting moisture. Condensed whey at 20% solids is estimated to contain 15.5% lactose.
[4] Average composition of reduced-lactose whey and reduced-mineral whey.
[5] Uses composition for WPC-34.
[6] Uses composition for WPC-80.
[7] Uses composition for food-grade lactose (*Chandan*).

Table 4—Comparison of lactose volumes that may be used for ethanol production, 2003-2006

Item	2003	2004	2005	2006
	-----Million lbs-----			
Total lactose volume (estimated)	4,000	4,142	4,266	4,433
Lactose used in whey products (estimated):				
Condensed whey, solids content	89	71	61	83
Dry whey products				
Dry whey, Total	807	770	774	819
Reduced lactose & minerals	60	61	70	65
WPC, 25.0-49.9% protein	139	139	141	152
WPC, 50.0-89.9% protein	4	4	5	7
Whey protein isolates, 90.0% and higher	0	0	0	0
Lactose	608	659	707	731
Total lactose used in whey products[1]	1,707	1,703	1,759	1,857
Lactose volume unaccounted for that could be used for ethanol production	2,293	2,439	2,506	2,576
	-----Million gallons-----			
Potential volume of ethanol production (estimated)	182	195	199	203
Estimated actual production in 2006				8

[1] Items may not add to total due to rounding.

ing whey-ethanol production by reviewing the potential volume of ethanol from whey sources, the current processes of whey permeate to ethanol conversion, the economics of producing fuel ethanol from whey permeate, and the organization of whey-ethanol plant operation in which dairy cooperatives may play a role.

Potential Volume of Ethanol From Whey Sources

Ethanol from whey is produced by fermenting the lactose contained in whey, whey permeate, or permeate mother liquor. Therefore, the potential volume of ethanol production from whey feedstock depends on the available volume of surplus lactose that is not used in whey-derived products.

Volume of surplus lactose. The 90.5 billion pounds of whey generated by the cheese industry in 2006 contained an estimated 4,433 million pounds of lactose (Table 3, *opposite*). An estimated total of 1,857 million pounds, or 42 percent of available lactose, was used in these main whey products: condensed whey, dry whey, reduced lactose and minerals whey, whey protein concentrates, whey protein isolates, and lactose.

Hence, an estimated 2,576 million pounds of lactose was unaccounted for in 2006 by these whey products. Some of this unaccounted for volume could have been in secondary and tertiary whey products and other whey or lactose-derived products. Therefore, it may be reasonable to estimate that there was about 2.5 billion pounds of surplus lactose in 2006. This is the amount of lactose that may be available for ethanol production.

Potential ethanol volume. Theoretically, 1 pound of lactose would yield 0.538 pound of ethanol. Therefore, the potential volume of ethanol production from surplus lactose in 2006 may be estimated at about 203 million gallons.

In the same way, potential ethanol volumes from surplus lactose were estimated for previous years: 182 million gallons in 2003, 195 million gallons in 2004, and 199 million gallons in 2005 (Table 4, *opposite*). The 2006 volume was a 12-percent increase from 2003.

In 2006, the two ethanol plants operated by dairy cooperatives together produced 8 million gallons of ethanol. That still left 195 million gallons as untapped potential.

Implicit in the estimation of potential ethanol volume is the premise that use of lactose in food, feed, industrial, and other applications should take precedent, and ethanol production is the last-resort use of whey and lactose. As will be seen later in the discussion of the economics of whey-ethanol production, every cent of net lactose value (price of lactose net of processor's cost) would increase feedstock cost of ethanol fermentation by at least 12.29 cents per gallon of ethanol. Last-resort use of whey and lactose in ethanol production would keep the feedstock cost as low as possible.

Share of dairy cooperatives. Dairy cooperatives produced 40 percent of the Nation's natural cheese in 2002 (*Ling*). Presumably, they also accounted for 40 percent of the whey generated. In that same year, dairy cooperatives produced 1.1 billion pounds of dry whey products, or 52 percent of U.S. total volume, in 28 dry whey plants that they operated.

Using these same ratios for 2006, dairy cooperatives would account for an estimated 800 million pounds of lactose that was not used in whey products. Of this amount, about 100 million pounds was used to produce 8 million gallons of ethanol by the two plants operated by dairy cooperatives. The remaining 700 million pounds of lactose represents a potential volume of 57 million gallons of ethanol.

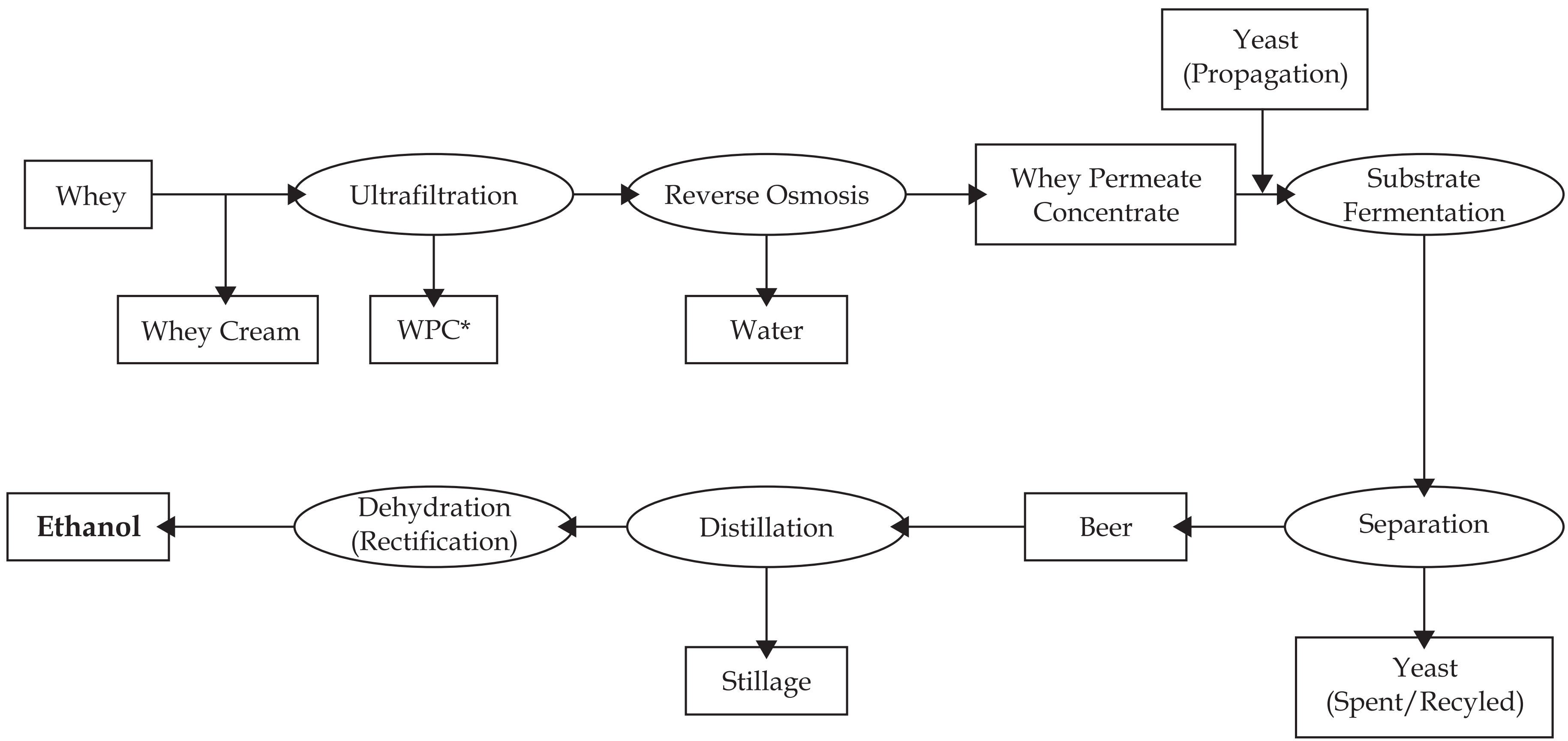
Processes of Whey Permeate to Ethanol Conversion

The first patent for the use of whey in ethanol production (*U.S. Patent no. 2,183,141*) was granted in 1939 (*Murtagh*).

The best known commercial process of producing ethanol from fermenting whey is the Carbery process, which was developed in Ireland for making potable alcohol and was later adopted for industrial alcohol and fuel ethanol as well.

In the United States, there is the proprietary process used by the plant in Melrose, Minn. In addition, research efforts have culminated in the development of some successful processes (*Dale, et al; U.S. Department of Energy (DOE), Office of Industrial Technologies, Energy Efficiency and Renewable Energy; Bio-Process Innovation, Inc.*). Many novel processes also have been seen in media reports and research literature.

Figure 2 -- Basic steps of whey-ethanol production



*WPC: Whey protein concentrate

The Basics. Ethanol production processes may vary between plants, but they all share some basic principles and steps (Figure 2).

After whey protein has been harvested from whey by ultrafiltration, the remaining permeate is concentrated by reverse osmosis to attain higher lactose content for efficient fermentation.

Lactose in whey permeate is fermented with some special strains of the yeast *Kluyveromyces marxianus* that are efficient in fermenting lactose. The yeast is added to the fermenting substrate and pumped to the fermentation vessels.

Once the fermentation has been completed, yeast is separated from the fermented substrate, and the remaining liquid (beer) is moved to the distillation process to extract ethanol. This ethanol is then sent through the rectifier for dehydration. If the resulting anhydrous ethanol is intended for fuel, it is denatured by adding gasoline to prevent misuse.

The effluent—the remaining liquid after ethanol has been removed from the beer (stillage) and the biomass (spent yeast)—may be discharged to a treatment system, digested for methane gas, sold as feed, or further processed into food, feed, or other products. (For a concise description of the manufacture of ethanol from whey, see *Hamilton*.)

Beyond the basics, there are many variations of whey-ethanol production processes. Two with available current information are the Carbery process and the processes offered by the Bio-Process Innovation, Inc. They are described in Appendix I and Appendix II, respectively.

Conversion factors used in this report

- One pound of lactose consumed in fermentation yields 0.538 pound of ethanol (theoretical yield).
- 1 liter of ethanol equals 0.7924 kilogram of ethanol.
- 1 gallon equals 3.785 liters
- 1 kilogram equals 2.2046 pounds
- 1 gallon of ethanol weighs 2.9992 kilogram or 6.6121 pounds.

The Economics of Producing Fuel Ethanol From Whey Permeate

Estimated cost of producing fuel ethanol from whey permeate. With only two industrial-scale whey-to-ethanol plants in the United States, no publicly available production cost data exist. Costs quoted by several sources do not have enough details and probably represent the best "educated" estimates. However, a recent comprehensive cost estimate of producing fuel ethanol from whey is publicly available in a June 2005 New Zealand report (*Waste Solutions Ltd*.).

The New Zealand report related that the estimated "at-gate" cost (operating and capital service costs) of producing ethanol from whey permeate at maximum technical potential, with a level of uncertainty of +/- 20 percent, was N.Z. $0.6-0.7 per liter. Using a currency exchange rate of N.Z. $1 = U.S. $0.7, the estimated cost translated to U.S. $1.60-1.85 per gallon.

The estimated cost took into consideration economy-of-scale effects, transportation costs, and competing waste uses, and included the following scenario and assumptions:

- Fermentation at local plants.
- Distillation to 96-percent ethanol at local plants.
- Transportation of 96-percent ethanol to a centrally located dehydration plant.
- Capital service cost per year was 20 percent of capital cost, assuming a mixture of debt and equity financing and a nominal interest rate of 10 percent.
- To be economically feasible, the dehydration plant needed to have a minimum daily capacity of 60,000 liters of ethanol (about 15,850 gallons a day or 5 million gallons a year).
- For alcohol recovery (distillation and dehydration), biogas from effluent treatment was used as fuel. (Surplus steam from the dairy plant or cogeneration plant would also help.)
- Wet feedstock that had at least 15 percent (by weight) fermentable sugar content could pro duce ethanol that was 9-10 percent (by volume) of the fermentation beer. The resulting ethanol recovery cost could be less than N.Z. $0.2 per liter (U.S. $0.52 per gallon). (For a beer that contained 3-4 percent ethanol, the ethanol recovery cost was at least N.Z. $0.54 per liter (U.S. $1.42 per gallon).)

The cost of producing ethanol from whey permeate estimated by the New Zealand report, at U.S. $1.60-1.85 per gallon, with a level of uncertainty of +/- 20

Table 5—Lactose input and estimated feedstock cost per gallon of ethanol at selected yield level

Ethanol yield (Percent of theoretical yield)	Lactose input (Pounds per gallon ethanol)	Feedstock cost per gallon ethanol (For every $0.01 net lactose value per pound)
100%	12.29	$0.1229
95%	12.94	$0.1294
90%	13.66	$0.1366
85%	14.46	$0.1446

percent, is similar to the costs quoted by sources in the United States. Estimates from these U.S. sources yielded an operating cost of about $1 per gallon. In addition, there was a capital service cost of between $0.30 and $0.80 per gallon, which was calculated at an assumed rate of 20 percent of capital cost. The capital service cost would have been higher or lower if the assumed rate had been different. Capital cost (cost of the plant construction project) had quite a wide range, from $1.50 to $4 per annual gallon for a commercial operation, depending on the scale of the plant.

Cost of whey permeate as feedstock. The amount of lactose needed to produce a gallon of ethanol depends on the level at which the lactose is consumed in fermentation and the efficiency of ethanol conversion. It was reported in the 1990s that commercial plants fermenting natural-strength whey could utilize greater than 95 percent of lactose with a conversion efficiency of 80-85 percent of the theoretical value (*Mawson*).

With technology advancement over the years and using higher concentration of lactose for fermentation, lactose consumption in fermentation is nearly complete at the two U.S. commercial plants. Presumably, the conversion efficiency is also higher than in the 1990s. The actual yield is proprietary information and is therefore not available.

For reference purposes, it was reported that conversion of lactose to ethanol at 85.5 percent to 91 percent efficiency (0.46 to 0.49 gram ethanol per gram lactose) could be obtained (*Dale*).

It would take 12.29 pounds of lactose to produce a gallon of ethanol, if the lactose is completely consumed in fermentation and ethanol conversion is 100 percent of the theoretical yield (Table 5).

The estimated operating cost of $1 per gallon of ethanol assumes that whey permeate used in ethanol fermentation is a free (no cost) feedstock. This assumption is valid when there is surplus whey to be disposed of by any least-cost means. However, when whey powder and lactose have found wider uses and have increased in value, the determination of the cost of whey permeate as feedstock for ethanol fermentation becomes more complicated.

To illustrate the calculation, use, for example, a May 2007 lactose price of $0.9370 per pound (Table 2). Subtracting from this price an estimated processor cost of $0.20 per pound for crystallizing and drying lactose, the net value of lactose was $0.7370. For every $0.01 net lactose value, the feedstock cost for fermentation would be $0.1229 per gallon of ethanol (Table 5). Given that the net value of lactose was $0.7370 per pound, the feedstock cost would amount to $9.06 per gallon of ethanol (($0.7370/$0.01)*$0.1229). If lactose consumption is less than complete in fermentation and ethanol conversion is less than 100 percent of the theoretical yield, then more than 12.29 pounds of lactose is required to produce a gallon of ethanol, and the feedstock cost would be even higher.

(No publicly available processor cost data for lactose production is available. The $0.20 per pound estimate is used, considering make-allowances of $0.1956 for dry whey in the Federal Milk Market Orders (*U.S. Department of Agriculture, Agricultural Marketing Service*) and $0.267 for skim whey powder in California's Stabilization and Marketing Plans for Market Milk (*California Department of Food and Agriculture)*).

Another illustration could use the lactose price prior to the run-up of whey products prices in 2006. The 2005 annual average price of lactose was $0.2012 per pound (Table 2). The net value of lactose after allowing for $0.20 processor cost would be $0.0012 per pound. The opportunity cost of lactose as feedstock for fermentation would have been $0.015 per gallon of ethanol (($0.0012/.$0.01)*$0.1229), or almost zero.

The calculation of the opportunity cost of lactose for ethanol fermentation is valid only if there are competing uses of the same lactose, such as manufacturing dry whey, lactose, or other whey products. If there is no such competition, then the whey permeate some-

Table 6—Whey products production by product and month, United States, 2006-2007

Product and month	By Month 2006	By Month 2007	By Month Change	Cumulative 2006	Cumulative 2007	Cumulative Change
	-- 1,000 pounds --		*Percent*	*-- 1,000 pounds --*		*Percent*
Dry whey, total[1]						
Jan	88,391	96,145	8.8	88,391	96,145	8.8
Feb	89,695	90,232	0.6	178,086	186,377	4.7
Mar	100,953	98,713	-2.2	279,039	285,090	2.2
Apr	95,662	96,818	1.2	374,701	381,908	1.9
May	97,295	99,198	2.0	471,996	481,106	1.9
Jun	89,701	94,628	5.5	561,697	575,734	2.5
Jul	95,226			656,923		
Aug	91,547			748,470		
Sep	86,271			834,741		
Oct	87,434			922,175		
Nov	85,865			1,008,040		
Dec	92,306			1,100,346		
Lactose, human & animal						
Jan	64,539	65,064	0.8	64,539	65,064	0.8
Feb	56,311	59,671	6.0	120,850	124,735	3.2
Mar	62,165	64,975	4.5	183,015	189,710	3.7
Apr	63,402	63,083	-0.5	246,417	252,793	2.6
May	66,057	67,145	1.6	312,474	319,938	2.4
Jun	60,027	62,013	3.3	372,501	381,951	2.5
Jul	60,333			432,834		
Aug	64,225			497,059		
Sep	58,964			556,023		
Oct	62,296			618,319		
Nov	60,505			678,824		
Dec	59,832			738,656		
Whey protein concentrate, total						
Jan	37,162	33,055	-11.1	37,162	33,055	-11.1
Feb	34,436	29,432	-14.5	71,598	62,487	-12.7
Mar	37,766	35,038	-7.2	109,364	97,525	-10.8
Apr	37,525	33,188	-11.6	146,889	130,713	-11.0
May	37,373	33,436	-10.5	184,262	164,149	-10.9
Jun	36,190	33,672	-7.0	220,452	197,821	-10.3
Jul	35,704			256,156		
Aug	35,024			291,180		
Sep	34,581			325,761		
Oct	34,581			360,342		
Nov	33,116			393,458		
Dec	34,266			427,724		

[1] Excludes all modified dry whey products.
Source: Dairy Products, September 2007, USDA National Agricultural Statistics Service.

how has to be disposed of and the opportunity cost of lactose for ethanol fermentation is likely to be zero or even negative.

As shown in Table 3, an estimated 1,857 million pounds of lactose were used in various whey products in 2006, and an estimated 2,576 million pounds (58 percent of total available lactose) were unaccounted for. Most of the unaccounted-for volume was likely to have been disposed of as waste. Accordingly, the lactose in this surplus whey would not carry an opportunity cost had it been used as feedstock for ethanol fermentation.

Nationally, the surplus whey situation will persist for the foreseeable future. Although prices of whey products have more than doubled since June 2006 (Table 2), whey products production has remained rather constant (Table 6, *previous page*). For the first 6 months of 2007, cumulative production of dry whey and lactose, respectively, was 2.5 percent higher than the amount of the same period last year, but whey protein concentrate was 10.3 percent lower. The combined volume of the 3 products for the 6 months in 2007, at 1,156 million pounds, was only 0.9 million pounds more than the same period in 2006.

In the short run, whey products manufacture is limited by the available plant capacity and the production volume can increase only marginally. This is because current whey products plants were built to operate at or near capacity. New investment to expand the capacity will not happen unless the industry is convinced that the recent price hikes are a long-term trend.

Although nationally whey is still in a surplus situation, its availability is often localized (regionalized). The cost of using it as feedstock for ethanol fermentation is therefore site specific.

Economic feasibility of producing fuel ethanol from whey permeate. Whether it is economically feasible to produce ethanol from whey permeate is determined by the balance of the costs and the expected revenues. Key components on the cost side are:

- Feedstock cost: Cost of whey permeate (lactose) as input for ethanol fermentation.
- Operating cost: Labor, energy, supplies, repair and maintenance, depreciation, insurance, licensing fees, etc.
- Capital service cost: Annual cost is calculated at a rate of capital cost prescribed by the decisionmaker, based on the opportunity cost (interest cost) of capital and risk premium for undertaking the investment. It may be at 10 percent of capital cost, 15 percent, 20 percent, or some other rate.

On the revenue side, there are three main considerations:

- Ethanol price: About 90 to 95 percent of ethanol is sold under long-term contracts (6 to 12 months). Many of these contracts are fixed-price. The remaining amount is sold on the spot market, and the spot-market prices fluctuate according to market conditions (*Renewable Fuels Association*). *The Annual Energy Outlook 2007 with Projections to 2030* forecasts ethanol wholesale price (in 2005 dollars) to be $2.520 per gallon in 2007, $2.066 in 2008, $2.099 in 2009, $1.814 in 2010, and $1.742 in 2011. Thereafter, the long-term trend is for the price to be in the $1.650 to $1.720 range (*DOE Energy Information Administration*).
- Byproducts value: Effluent dried as feed, digested for methane gas, or used for other purposes, with positive or negative returns.
- Incentives: Currently (through December 31, 2010) there is a small ethanol producer Federal tax credit of $0.10 per gallon, up to 15 million gallons or $1.5 million per year, for a production facility with up to 60 million gallons of annual production capacity (26 U.S.C. § 40. The citation is intended for information only. Please consult tax professionals for specific tax treatments.) Various grants, loans, and other incentives are also offered by various Federal and State programs.

Depending on the magnitude of capital service cost and assuming whey permeate is a free feedstock that is converted to ethanol at an operating cost of $1 per gallon, the ethanol price must be higher than the total cost of producing it for the new investment in the ethanol plant to be economically feasible. Various production incentives may lower the price level required for economic feasibility.

Net returns from the ethanol enterprise should be measured against the profitability of making other whey or whey-derived products or of other uses of whey, to determine whether ethanol production is a more worthwhile undertaking. A further consideration should be which of the whey enterprises fits best with a cooperative's overall business strategy.

Economy of scale. Because whey contains about 93.5 percent water and only 4.9 percent lactose, even a whey-ethanol plant of modest size requires a very large cheese operation to provide whey for feedstock. This fact destines the scale of whey-ethanol plants to be much smaller in size than present-day corn-ethanol plants and higher in capital cost per annual gallon.

A larger scale whey-ethanol plant would benefit from scale economy, where the capital cost increases proportionately less than the increase in plant size, resulting in lower capital cost per annual gallon. In a joint project studying the cost of producing ethanol from corn and lignocellulosic feedstocks, researchers at USDA and DOE used the following expression for scaling capital cost for equipment:

$$\text{New cost} = \text{Original cost} \times (\text{new size}/\text{original size})^{\text{exponent}}$$

The joint report cited USDA's value of the scaling exponent of 0.6 and DOE's average value of 0.63; both were within the range of 0.6 to 0.7 commonly cited in cost estimation literature (*McAloon,, et al*).

Another estimate based on 19 corn-ethanol plants built between 1996 and 2004 and ranging in size from 15 million to 50 million gallons per year yielded a plant scaling exponent value of 0.77 (*(S&T)[2] Consultants , Inc., et al*).

Regardless of the value of the scaling exponent, as long as it is less than one, there would be scale economy for plants that lie within the relevant size range. Although this reference is to plants making ethanol from corn starch and lignocellulosic feedstocks, it is reasonable to expect that a similar economy of scale would apply to whey-ethanol plants.

A larger sized whey-ethanol plant would lower the per-gallon capital cost, but also would require a larger whey volume, either from a larger-sized cheese plant or from a group of cheese plants.

Whey-Ethanol Plant Scenarios and Roles of Dairy Cooperatives

The New Zealand report suggested an ethanol plant with a minimum annual capacity of 5 million gallons. Assuming lactose is completely consumed in fermentation and ethanol is produced at the level of the theoretical yield, the plant would require 195,000 pounds of lactose a day as input.

A cheese-whey/ethanol complex. A cheese plant with a daily capacity of processing 4.5 million pounds of milk—about the size of some of the largest cheese plants in the United States—would generate four million pounds of whey to supply the required 195,000 pounds of lactose to the ethanol plant. To pump over whey permeate and save on transportation costs, the ethanol plant should be located close to the cheese plant.

The setups of the two U.S. whey-ethanol plants, at Corona and Melrose, fit this single cheese-whey/ethanol plant complex scenario.

Multi-plant coordination. For cheese plants of more modest sizes (typically located in the more traditional dairy regions), assembling whey permeate for ethanol production would require coordination among plants. For example, three plants, each with a daily capacity of processing 1.5-2 million pounds of milk into cheese, would yield the necessary amount of whey to supply lactose to the ethanol plant. At each cheese plant, whey would be ultrafiltered (deproteinated) and the permeate would be concentrated by reverse osmosis to about 20 percent solids (15 percent lactose) and then shipped to the ethanol plant for fermentation. To reduce whey permeate shipping costs, the ethanol plant should be located adjacent to the largest cheese plant among the three or where it is most logical and appropriate.

This coordination scheme, in fact, has been in practice by dairy cooperatives for whey handling, where several cheese plants condense their whey and then ship the condensed whey (deproteinated or otherwise) to a whey powder plant for drying. The same scheme could be used to coordinate whey handling among cheese plants to supply a whey-ethanol plant. Furthermore, such a coordination scheme could be expanded to allow future whey-ethanol plants to be of greater capacity in order to take advantage of the economy of scale.

Roles of dairy cooperatives. If a new whey-ethanol plant is proved to be economically feasible and were to be built, the enterprise might be organized according to these forms:

- An ethanol plant adjacent to a dairy cooperative's large cheese plant, similar to the setups of the two existing plants.
- An ethanol plant that ferments whey permeate assembled from several cheese plants of a dairy cooperative.
- An ethanol plant that ferments whey permeate assembled from several cheese plants. The coordination of whey handling may be among a cooperative's and other cooperatives' cheese plants, or among a cooperative's and other cooperative and non-cooperative entities' cheese plants. The coordination may be carried out by contract or organized as a joint venture. Small cheese plants looking for opportunities to add value to whey may be inclined to participate in such undertaking.

Some Specific Issues in Whey-Ethanol Production

Because of the composition of whey, there are some issues that are specific to whey-ethanol production (*Dale*):

- Whey and whey permeate concentrate are very susceptible to contamination and spoilage.
- Whey permeate concentrate is costly to transport (mostly water).
- The fermentation is susceptible to lactic contamination. The fermentation systems must be very carefully designed and operated, basically to food-grade cleanliness or, for some systems, even to aseptic standards.
- Because the calcium salts in the whey are "reverse soluble"—becoming insoluble at higher temperatures—scaling of the distillation column could be a problem or a cause for concern.
- The effluent is high in chloride. This limits the rate of application on fields if land-spreading is used. Just land-spreading of the effluent can be a major operating cost. There are two ideas for higher value products from the spent effluent: (1) a base for a sports drink if whey permeate concentrate is the substrate, and (2) a mineral salt block for animals if permeate mother liquor is the substrate.

Some Historical Lessons

In the United States, fuel ethanol production started in the late 1970s. During the 1980s, about 165 commercial plants (plants with more than 500,000 gallons annual capacity) were constructed, with grain as the primary feedstock. By the end of 1990, fewer than 40 plants remained in operation (*Murtagh, et al*), although annual ethanol production grew to 900 million gallons (*Renewable Fuel Association*).

The reasons for the high attrition rate of plants during that decade were reviewed in a 1991 paper (*Murtagh, et al*). Experiences of that period may be relevant to future commercial whey-ethanol development and are summarized in this section. They may provide some useful lessons that illustrate the kind of mistakes to avoid.

The most significant causes of project failures during the 1980s were improper technology selection and improper engineering design. Every aspect of the plant operations was susceptible to such failures. From feedstock pretreatment to yeast propagation, fermentation, distillation, DDGS (distillers dried grains with solubles) drying and storage, and piping, the culpable factors were inadequate design, equipment, and/or process. Without being supported by adequate research, novel steps taken to save cost, increase yield, or otherwise cut corners, tended to invite disastrous results.

Other factors that contributed to failures were shifting public policy; fraudulent investment schemes; plants that were constructed with high cost, without feasibility studies, or without adequate financing; and lack of technical and managerial expertise in the biochemical process.

Conclusions

There is a potential for supplementing the Nation's fuel ethanol supply by an estimated 203 million gallons a year (2006 data) if all lactose in surplus whey and whey permeate—whey that is not used in value-added whey-derived products—is fermented for the purpose. Dairy cooperatives could have a share of 65 million gallons of this potential. However, there are only two commercial whey-ethanol plants with an annual production of 8 million gallons. Both plants are currently owned and operated by dairy cooperatives.

The fact that the two plants have been in operation for more than 20 years is an indication that (1) fuel ethanol production from whey is technically feasible, (2) whey-to-fuel ethanol production technologies and processes are mature and capable of being adopted for commercial operations, and (3) producing fuel ethanol from whey is economically feasible.

Because there are no publicly available, actual production-cost data, no attempt was made to estimate the profitability of the whey-to-ethanol enterprise. The cost of producing ethanol from whey permeate estimated by the 2005 New Zealand report was U.S. $1.60-1.85 per gallon (at a currency exchange rate of N.Z. $1 = U.S. $0.7), with a level of uncertainty of +/- 20 percent. Estimates ascertained from U.S. sources in the course of this study yielded a per-gallon operating cost of about $1 and a capital service cost that may be calculated on a capital cost of $1.50 to $4 per annual gallon. These cost estimates have a wide range of uncertainties and are also sensitive to the scale of the plant.

Then there is also the uncertainty regarding the cost of using whey permeate as feedstock. Prior to the price run-up in 2006, the dairy industry's main task concerning whey had been to seek more methods for whey to be useful and valuable. Under those circumstances, whey and whey permeate used in fermentation may be regarded as a feedstock of no or even negative cost. This free feedstock premise remains true if there are no readily accessible, profitable alternatives for the whey.

In assessing the feasibility of a new whey-ethanol plant, the cost of whey permeate as feedstock needs to be carefully evaluated in this era of whey products' price uncertainties. Every 1 cent of net lactose value from alternative uses would increase the fermentation feedstock cost by at least 12.29 cents per gallon of ethanol. Other important factors to consider besides feedstock cost are (1) an appropriate plant scale that would minimize capital cost and the cost of assembling feedstock, (2) an appropriate technology and process specifically for whey-ethanol production that would minimize operating cost, (3) best alternatives for using and/or disposing of the effluent, (4) ethanol price, and (5) various government production incentives.

The *OECD-FAO Agricultural Outlook 2007-2016* provides the only available long-term dry whey price projection. It forecasts the wholesale price of edible dry whey (F.O.B., Wisconsin plant) to peak in 2011, but the decline afterwards will still see the 2016 price to be 20 percent higher than in 2006 (*OECD-FAO*). On the other hand, the *Annual Energy Outlook 2007 with Projections to 2030* forecasts the ethanol wholesale price to peak in 2007 ($2.520 per gallon) and fluctuate in the $1.650 to $1.720 range after 2011 (*DOE Energy Information Administration*). However, care should be used if the two projected price series are to be employed for evaluating the feasibility of a new whey-ethanol plant versus a new dry whey plant, because the forecast of the dry whey price is in nominal dollar and the ethanol price is in constant (2005) dollar. Further complicating the picture is that the projection of the dry whey price preceded, and therefore did not incorporate, the unexpected price surges in 2007.

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Appendix I. The Carbery Process

The Carbery process in its present-day operation is provided by the Carbery Group (formerly Carbery Milk Products Ltd.), Ballineen, County Cork, Ireland (*Desmond*, used with permission).

"In the alcohol plan the raw material, whey permeate, is converted into finished product, potable alcohol. The first step in this process is the conversion of the carbohydrate in the permeate (lactose) into ethyl alcohol. This is achieved by fermentation with a specific yeast strain.

The fermentation is carried out in eleven cylin dro-conical fermenter vessels. Compressed air is used to agitate the contents of the vessel and it also provides aeration of the contents to encourage continued yeast growth.

Whey permeate and yeast are added together into a fermenter and the fermentation is allowed to proceed under the optimum conditions of temperature, pressure and agitation, until all of the lactose in the permeate has been exhausted. The lactose is converted mainly into ethyl alcohol, but other compounds known as congeners are also produced by the fermentation. Depending on the initial lactose concentration and yeast activity, the fermentation will take between 12 and 20 hours to complete.

After fermentation, the contents of the fermenter are referred to as 'wash' or 'beer.' The alcohol content of the wash will depend upon the initial lactose concentration in the permeate and the fermentation efficiency. The wash is pumped to the distillation plant.

The next operational step performed on the wash is distillation. The purpose of the distillation step is to concentrate the alcohol portion of the wash, and to remove the congeners formed during fermentation. A continuous-distillation process employing column stills is used. It consists of three sections:

i) Beerstill.
ii) Extractive-distillation unit.
iii) Rectifier.

In the beerstill, the wash is concentrated to 96 percent alcohol. This is then fed to the extractive-distillation column where water is added, changing the boiling point of the mixture, so that high-boiling-point 'higher alcohols' may be removed. Finally, in the rectifier, the alcohol strength which has been reduced in the extractive-distillation column is increased again to 96 percent. Other congeners such as 'heads', 'esters' and 'fusel oil' are also removed in this final rectifier.

Most distillation units consist of a cylindrical, vertical column. Perforated plates (sieve trays) are fixed horizontally at intervals of several inches throughout the height of the column. Liquid is usually introduced to a plate approximately half-way up the column. Steam is introduced at the base. The steam and vaporized liquid tend to rise up the column through the plate perforations, while the liquid tends to fall to the bottom via a series of down pipes.

Alcohol with a boiling point of 78°C is more volatile than the water portion. The alcohol will tend to rise up the column in the vapor whereas the water will tend to go down the column with the liquid. The alcohol is concentrated to 96 percent in a concentrating column. The product is removed to storage/further rectification, and spent wash, which contains very little alcohol, is removed from the bottom of the column.

Vapors rising above the top plate of the col umn are condensed in one or more condensers, and a reflux line returns the condensate to the uppermost plates, above the point where the product is drawn off, thus maintaining a liquid level on the draw tray."

Ardent readers will find the process has evolved over the years when compared with the original setup (*Sandbach*). It also should be noted that potable alcohol and fuel ethanol have different quality requirements, and the processes of producing them may differ somewhat, although the basic principles are the same.

In addition, for potable alcohol, ethanol concentrations post-fermentation typically range from 2.5 percent to 3.5 percent (*Desmond*). Fuel ethanol production requires ethanol content in the beer to be at least double that level for energy-efficient distillation and dehydration.

Appendix II. The Processes of Bio-Process Innovation, Inc.

The processes offered by Bio-Process Innovation, Inc. (BPI), are the culmination of many years of research (e.g., *Dale, et al*). Depending on the feedstock and efficiency desired by a plant, the company offers four kinds of fermentation systems (*Bio-Process Innovation, Inc.*):

1. **Immobilized Cell Reactor/Separator (ICRS)**
This patented immobilized cell reactor/separator separates ethanol as it is being produced and allows the quick and continuous conversion of clear whey permeate concentrate to ethanol. The experiment for the patent application (*U.S. Patent no. 4,665,027*) shows that it has an initial inlet lactose concentration of about double the natural lactose content in whey permeate and a sugar utilization rate of 98 percent. The outlet (effluent) BOD is about 2.5 percent of its original value.
2. **Continuous Stirred Reactor/Separator**
This technology allows high rates of fermentation coupled with ethanol recovery from the fermentation vessel. Yeast can be immobilized or recycled to keep fermentation rates high.
3. **Continuous Cascade Reactor**
Three or four stage continuous cascade fermentation system coupled with the company's proprietary salt and ethanol tolerant strains of *Kluyveromyces marxianus* (a lactose fermenting yeast family) allows 7 to 10 percent ethanol to be made from permeate mother liquor, whey permeate concentrate, or lactose. (*U.S. Department of Energy, Office of Industrial Technologies, Energy Efficiency and Renewable Energy* highlights the Continuous Cascade Reactor as a low-energy continuous system for converting waste biomass to ethanol.
4. **Batch Fermentation of Permeate Mother Liquor**

Actual performance for the fermentation systems two through four might be different from Immobilized Cell Reactor/Separator (system 1). But each of the four systems can attain near complete conversion of lactose to ethanol, at 0.46 to 0.49 gram ethanol per gram lactose. Outlet ethanol will be high if the process does not include simultaneous separation; low, if the technology is incorporated (*Dale*).

These associated technologies work with the above systems: (1) salt and ethanol tolerant strains of *Kluyveromyces marxianus*, (2) yeast production from whey permeate, and (3) low energy/non-fouling distillation of beers produced from whey permeate or permeate mother liquor.

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