Butanol: The Other Alternative Fuel

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As I motored from Blacklick to Brookings in my 100% butanol-fueled car, several questions occurred to me:

- How much sugar is available from the grasses growing along freeways and in pastures?
- How much energy would it take to process these grasses—with their high content of water and sugar—into butanol?
- Why haven't people recognized the fact that young grasses are low in lignin and cellulose?
- Why haven't people considered that it might be easier to use grass as a readily digestible feedstock for fermentation?
- Why haven't we considered the full potential of pastures, *e.g.* harvesting them four or five times per year as sources of biomass feedstock?

Similar questions led me to butanol 15 years ago.

Butanol is amazing. A gallon in the tank of my '92 Buick improves torque properties and mileage. Even though its BTU content is less than that of gasoline, it gives better mileage. My Buick averages 22 mpg with gasoline, whereas it averaged 25 mpg from Ohio on 100% butanol. Significantly, these results pertained without modification to the engine, whereas modifications are required for automobiles to use E85 (85% ethanol, 15% gasoline).

10,000 Miles Across America

I uncorked the butanol "genie" 2 years ago when I drove across the United States on 100% butanol in my 1992 Buick without any modification to the engine. That event demonstrated to the public that a power-grade fuel alcohol made from corn is already available —butanol—with the potential to replace gasoline, gallon for gallon.

On May 21, 2007, in Brookings, SD, we finished the first leg of our "2007: 2-K Second Run Across America." After two demonstration drives using 100% butanol as fuel, I contend that the sooner we start making ButylFuel™, the sooner you will be able to put it into your tank and help stop global warming.

The New Butanol Paradigm and Global Warming

Butanol can be used to power your current car. It is safer than gasoline, will give you better mileage and, above all, it will increase the amount of energy derived from biomass in comparison to ethanol—by 24–42%[1].

The following are questions I've asked over the past few years:

- What if we could make a transportation fuel from biomass that requires no engine modification and is safe?
- What if we could make a biomass fuel today that can solve most of the shortfalls of the other alternative fuels?
- Isn't this what our tax dollars have been searching for?

We could mitigate CO_2 emissions quickly by doing something that is applicable to every gasoline-consuming car already on the road. This is important, particularly in view of the fact that many people are resistant to buying flex-fuel cars that run on E85 or gasoline. People keep their old polluters because they cannot afford these new automobiles. Butanol would enable them to replace gasoline in their existing cars and, thereby, immediately help stop global warming.

Butanol could be introduced into the US fuel grid way beyond the blend of 90% gasoline and 10% ethanol (E10). Higher percentages of ethanol can be burned only in flex-fuel cars. In contrast, we could begin introducing various blends of butanol with gasoline, up to 100% (Bu100). And, as I demonstrated with my 2005 trip across America, and my 2007 drive to South Dakota, we can already run fuel-injected cars with Bu100 in the fuel tank, without engine modification.

Safety

In comparison to gasoline and ethanol, butanol is hard to ignite and it burns with a cleaner flame; it is combustible but not dangerously flammable as is gasoline and ethanol. Furthermore, again in contrast to ethanol, butanol can be shipped through existing oil pipelines without causing damage. However, butanol awareness is in its infancy and many unanswered questions remain.

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[1]Editors' note: Depending on whether and how hydrogen is captured, see Table 3.

Attempts to Commercialize

From 1998 to 2003, as I progressed to phase III of a DOE grant, my goal was to commercialize. Two venture capitalists (VCs) decided against investing. One reason was that butanol was not on the National Renewable Energy Laboratory (NREL) or Department of Energy (DOE) databases—no mention of it as an alternative fuel could be found.

The International Clostridia Group had been trying for over 25 years to obtain recognition regarding butanol fermentation; individuals interested only in ethanol had ignored them. Research follows funding, and funding follows extensive lobbying which occurred from groups pushing ethanol research and implementation. At the time, no lobby was pushing for butanol. In fact, we still don't have a butanol lobby, despite a critical need.

Absent the lobby, and out of frustration to try to get the NREL, DOE, and investors to understand the efficacy of butanol, and having used butanol in my John Deere tractor and lawnmower, I finally realized that I had to bite the bullet, and test it in the family car. I put 100% butyl alcohol into the fuel tank of my 1992 Buick and drove across America, coast to coast, during the summer of 2005.

Pollution Reduction

Before the across-US trip, I drove to the EPA station in Springfield, OH, using butanol I had made in the lab from sugar and corn. They were amazed by the test results: butanol reduced hydrocarbons by 95%, carbon monoxide to 0.01%, and oxides of nitrogen by 37% compared to gasoline. My 13-year-old Buick had never performed so well as during that 120-mile roundtrip.

The EPA staff in Springfield were so impressed by the results that they arranged for free tests at EPA stations in other states. The Springfield results were repeated; my 100%-butanol-fueled car was well below the minimum pollution-emission standards at each testing station.

At that point, I put "Powered by 100% Butanol" signs on the doors and headed to the St. Louis arch, to Albuquerque, the Grand Canyon, Phoenix and on to San Diego. We drove up Mount Palomar, home of the 200-inch Hale telescope, then up and over the Los Angeles Grapevine into Sacramento and San Francisco; then eastward we went, to Washington, DC.

Why Not Butanol in the 1970s?

Butanol amazes others too. People are surprised to learn that it hasn't been firmly on the radar screen as an alternative fuel. On the other hand, butanol *was* on the alternative-fuels map three decades ago. We had a choice to subsidize either ethanol or butanol and we went with ethanol. Produced by the historic "ABE" fermentation process (developed 1919–1920), butanol has been viewed as too expensive to manufacture via fermentation, and too difficult to recover—which it was. On the other hand, bacteria continuously synthesize acetone, butanol and ethanol (ABE) in anaerobic soils and even in manure heaps. So if nature can make butanol and butanol can power my car, "How soon can I make more butanol?" That was my question 15 years ago.

Table 1 provides concentrations, boiling points and yields of ButylFuel™ compared with ethanol and with data for the ABE process. The reasons we did not go with butanol in the 1970s were:

- The ABE fermentation process yields only 1.3 gallons of butanol/bushel of corn, whereas yeast fermentation produces 2.5[2] gallons of ethanol/bushel of corn.
- Its low final concentration (0.6%) compares poorly with that of ethanol from yeast fermentation (10–15%); the 1–2% alcohol concentration in the ABE-fermentation combination is sufficient to kill the fermenting bacteria.
- Butanol's boiling point (117°C) is higher even than that of water. At the 1–2% final batch concentration, there is a lot of water to boil off, which is expensive.

Table 1. Comparison of yeast ethanol, ABE fermentation and ButylFuel™.

	Ethanol	ABE			ButylFuel™ butanol only
		Acetone	Butanol	Ethanol	
Final concentration* (%)	10–15	0.3	0.6	0.1	(continuous)
Boiling point (°C)	78.5	56.5	117	78.5	117
Yield (gallons/bushel corn)	2.5[2]	0.70	1.3	0.36	2.5

*Final concentration is the proportion of alcohol to total solution. The ABE process requires a much greater amount of water and thus a much larger facility to produce half the alcohol. This is because anything more than 1–2% concentration kills the bacteria in the ABE process.

Solving Three Problems With One Patent

I asked a simple question: "How could butanol yield be increased and production costs decreased?" I solved the three major problems with the ABE process by:

- increasing the yield of butanol from 1.3 gallons/bushel of corn to 2.5 (thus making it similar to that of ethanol by yeast fermentation);
- overcoming the problem of the low final concentration of 1–2% by developing a recovery process that removes the solvents continuously and precludes accumulation to a level lethal to the microbe; and
- solving the expensive recovery problem associated with the high boiling point by sparging carbon dioxide (produced by the fermentation) through the broth, stripping the butanol and then letting a gravity process increase the concentration before removing the remaining water.

[2]Editors' note: A conversion rate of 2.8 gallons of ethanol/bushel of corn is generally used (*e.g.* http://www.ethanolmarket.com/corngrains.html), potentially applicable also in Tables 2 and 3.

Development of the continuous operation eliminated the need for the batch-process clean up every 4–5 days and having to restart the fermentation, as are normal with the ethanol process.

Making Butanol Only

As a physicist, my question was, "Where is all the precious carbon (sugar) in the feedstock going?" The carbon was being used to produce ancillary (undesired) products unnecessary for butanol production. In the ABE process, much of the carbon goes into acetic, lactic, propionic and butyric acids. As the pH drops, the bacteria change morphology and enter a solventogenic phase in which they convert the acids to acetone, ethanol, isopropanol and butanol. The production of butyric acid makes possible the synthesis of butanol. Therefore, I posed another scientific question: "Is it possible to convert carbon (sugar) directly to butyric acid and then to butanol?" In addressing this question, I hypothesized that butyric acid would be converted to butanol; accordingly I added butyric acid at a 3% concentration to an active wort and watched the microbes digest it and make butanol. Eureka! This became my patent. Notwithstanding the origin of the butyric acid, I was able to double the yield to 2.5 gallons of butanol/bushel (calculated) by eliminating the ancillary products (acetic, lactic and propionic acids, and acetone, ethanol and isopropyl alcohol) by a proprietary method. We now produce butyric acid, and continuously convert it to butanol.

More Energy From A Bushel of Corn; the New "Butanol Economy" Paradigm

Examining the various types of processing and focusing on energy content, Table 2 shows that 24% more energy is produced from a bushel of corn by producing butanol (a four-carbon molecule) rather than ethanol (a two-carbon molecule).

Table 2. Comparisons of accruals from corn.

		Gallons/bushel	BTUs/bushel
Ethanol		2.5	210,616
ABE	Acetone	0.59	141,583
	Butanol	1.35	51,845
	Ethanol	0.20	16,712
Total ABE		2.14	210,140
ButylFuel™	Butanol	2.5	262,056
[BTU difference, Butylfuel™–ethanol]			[51,440 (24%)]

Furthermore, hydrogen is generated in the anaerobic fermentation, adding 17–18% of energy captured (Table 3)

TABLE 3. ENERGY COMPARISONS, CORN-PRODUCED ETHANOL VS. THE BUTYLFUEL™ PROCESS.

	Corn	Ethanol	Butanol	Hydrogen	Increase
BTU/pound		12,790	15,511	61,000	
BTU/gallon		84,286	104,854		
Gallons/bushel of corn		2.5	2.5		
Pounds/gallon		6.59	6.76		
Pounds/bushel	56	16.5	16.9	0.62	
BTUs/bushel of corn		210,715	262,136	37,576	
BTU increase, butanol and hydrogen separately and cumulatively over ethanol (%)			24	18	42

The ButylFuel™ process generates hydrogen—which could be captured and used with the ButylFuel™ production facility—a potential capture of 18% more energy, for a total of 42% more energy compared to ethanol (Table 3). This increase is potentially significant in terms of reducing US reliance on foreign oil. Recently Steven Koonin (2006) stated:

> *Credible studies show that with plausible technology developments, biofuels could supply some 30% of global demand in an environmentally responsible manner without affecting food production.*

With the energy captured by the ButylFuel™ process—42% more than from ethanol—we should be able to supply substantially more than 30% of global demand.

Butanol acceptance and development are in their infancy. We still have to go through all levels of tier testing. I see future retrofitting of ethanol fermentation plants. The simple fact is: we capture 42% more energy from the same bushel of corn producing butanol via the ButylFuel™ process, and butanol can go directly into the automobile fuel tank. The sooner we implement this "New Butanol Economy" paradigm, the better it will be for the planet.

Small is Good—Powerful Microbes

Figure 1 shows a colony of microbes "huddled" where nutrients pass by and products of fermentation are washed away. This is the ButylFuel™ reactor—axenic and anaerobic.

Ethanol production requires less stringent conditions—pasteurization suffices rather than sterilization. Because of these different requirements, capital equipment investment will be necessary to retrofit ethanol plants for butanol production.

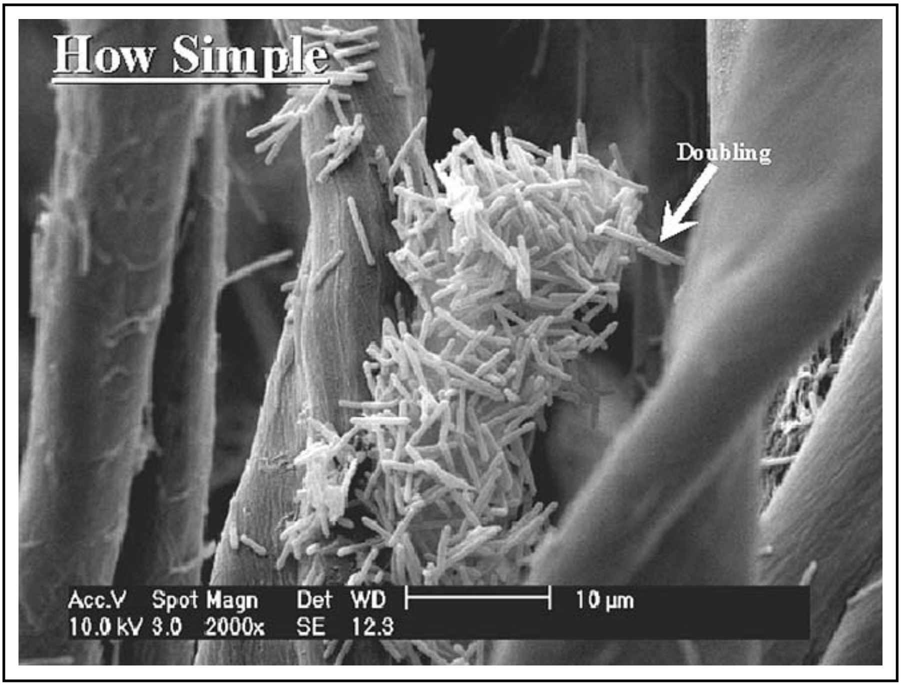

Figure 1. A colony of *Clostridium acetobutylicum* ATCC 824 on an inert cellulosic support, flushed with fresh feedstock and butanol continuously removed.

Bigger Is Better

Butanol is a 4-C molecule whereas ethanol has two C atoms. Table 4 shows that butanol's larger molecule translates into more energy: 110,000 BTUs/gallon versus 78,000 for ethanol. Table 4 shows also that butanol is safer to use than ethanol and gasoline as a result of its lower vapor pressure (VP)—it is difficult to ignite and it burns slowly. Like diesel, a match has to be held to it for ignition; butanol is combustible but not flammable, whereas methanol, ethanol and gasoline are flammable and potentially explosive.

Table 4. Properties of fuel-grade alcohols and gasoline.

	Methanol CH_3OH	**Ethanol** C_2H_5OH	**Butanol** C_4H_9OH	**Gasoline**
Energy content (BTUs/gallon)	63 k	84 k	110 k	115 k
Motor octane	91	92	94	96
Air:fuel ratio	6.6	9	11–12	12–15
Vapor pressure (psi@100°F)	4.6	2	0.33	4.5

Cost Per Mile

An average gasoline consumption of 22 mpg at $3.00/gallon means a cost of $0.14 per mile. Table 5 provides cost comparisons for gasoline, E85 and butanol.

The lower cost per mile with butanol (at $3.00/gallon) is encouraging. On the drive to Brookings, the Buick averaged 25 mpg, extrapolating to $0.12/mile, less than for E85 (at $2.80/gallon) or gasoline (at $3.00/gallon). On our cross-country trip in 2005, we got 27.5 mpg going through the desert, equivalent to $0.11/mile.

Table 5. Costs per mile for E85, gasoline and butanol.

			Cost/mile
Cost/gallon	E85	$2.80	
	Gasoline	$3.00	
	Butanol	$3.00	
Average mpg	E85	17.6*	$0.16
	Gasoline	22	$0.14
	Butanol	25	$0.12

*20% less than for gasoline.

Homeland Security, Energy Decentralization and the Farmstead

Presently, the United States needs a substitute for foreign oil to generate more energy independence and safely replace gasoline. And we want to revitalize the American farming industry by growing biomass locally and converting it locally to butanol. In doing so, we increase homeland security by decentralizing energy production and distribution. This is exactly what the United States wanted to do back in the 1970s with ethanol after the first OPEC crisis.

For improved security in transportation fuel, ButylFuel LLC proposes building turnkey platforms to enable farmsteads to produce value-added butanol for sale to the energy grid as well as to local communities. A 500-acre farm producing 120 bushels/acre of corn at $3.00/bushel will gross about $180,000 a year. In contrast, the same acreage and same yield, used to produce butanol at 2.5 gallons/bushel and sold to neighbors for automobile use at $3.00/gallon, would gross about $450,000. Of course, butanol production would entail additional capital.

With butanol, a new positive attitude will emerge from "Not in my backyard" to "Let's put one on my farm." An emerging positive and supportive grassroots attitude will make things happen quickly and help spread farmstead biorefineries across America.

ButylFuel™

ButylFuel LLC is gathering energy-balance data to compare the costs for producing butanol using the ButylFuel™ process versus ethanol manufacturing. At the same time, we are establishing the equipment necessary for stable long-term anaerobic, axenic manufacturing practices.

It is expected that initial capital-equipment costs will be more for butanol fermentation parlors because of the different requirements for batch yeast vs. continuous anaerobic butanol production. However, labor and other overheads will be reduced with the continuous process, therefore, encouraging data are expected from our work.

No matter what the biomass stream is, ethanol and butanol entail the same material handling costs up front (*i.e.* for grinding and pulverizing the feedstock). Similar distillation recoveries will be involved in the back-end processing; additionally, there will be similar by-product opportunities (for the unspent corn/distillers grains left over as well as for other solid-waste streams). Only the fermentation parlors will be modified for conversion from ethanol to butanol production.

Pretreatment of biomass produces sugars for digestion. Sugar is sugar. It doesn't matter whether it comes from kudzu or willow, corn kernels or stover, or anything else that grows on planet Earth. Research being done to turn various biomass feedstocks into sugars for ethanol is applicable to butanol production. It takes 14 lbs of sugar to make a gallon of either butanol or ethanol.

Missions

Our primary mission at ButylFuel™ is to stop global warming by impacting the existing automobile fleet. The sooner cars and airplanes begin using butanol, the sooner we will positively affect the planet's health.

We also vigorously promote an agricultural way of life and community throughout the United States by growing feedstock and disseminating ButylFuel™ from the farm. In the 1970s and 1980s, the government encouraged farmstead-ethanol production until several farmers were killed and it was shown that the energy-balance is unfavorable for small farmstead operations (Carley, 1981; Hunt, 1981).

Everyone at this conference wants to get out from underneath the oil thumb, and build US farming communities so that they have a stable and profitable income selling value-added products that will always be in high demand.

Strategy

Our strategy is to walk before we run, one step at a time. One step we will take is to scale up from our continuous 50 gallons/week process to a stable 100 gallons/week. Our next step will be to manufacture 1–2 million gallons/year as a pilot plant, using the feedstock slip-stream of an existing ethanol facility. Then we will raise butanol production to 10 million gallons/year.

The Future

A good farmer is nothing more nor less than a handy man with a sense of humus.

—E. B. White

We in the United States have been like Don Quixote on his noble quest to save Delcinea's honor. He mistook a windmill for another knight and ended up dueling the windmill. On our noble quest to save America's honor by producing energy from biomass, we have misinterpreted the viability of ethanol and missed the potential of butanol for three decades. Now, we have an opportunity to remedy this.

Not only did we miss butanol's feasibility as a fuel, but we should pay attention to an additional aspect of our "biomass to energy" quest—soil scientists are little involved. Where are they? Many scientists and engineers are focused on solving problems associated with lignin removal and with the use of stover, switchgrass and wood as biomass and their conversion to sugars. But, if we fail to restore the soil's humus and tilth with aerobic bacteria, 18–24 inches below the surface, we will be in trouble. If we are to leave a "biomass to fuel" legacy to our children, its viability will be determined by how much topsoil we bequeath.

As we compact the soil and deplete its trace minerals, air and nitrogen, its fertility is compromised. Bill Richards[3] mentioned that his tractor is equipped with a GPS system that doesn't allow him to take the same path twice through the field. That is great, but we should also make a concerted effort to rebuild the soil. No-till works only at the surface, preventing erosion; it does little to increase the depth of aerobic bacterial activity. A spin-off of good tilth is a soil that holds moisture more effectively, requires less application of chemical fertilizers and requires less energy to go through the field.

Since I demonstrated the efficacy of this other alternative fuel with my '92 Buick, many would rather build butanol plants than ethanol plants. I encourage them to build ethanol plants and, in due course, retrofit them to produce butanol. We've had 30 years of tax incentives to solve ethanol's problems, whereas butanol is in its early years.

Uncorking the butanol "genie" was a major turning point in the initial acceptance of butanol, stimulating such interest that every person who has ever written a paper about butanol or ABE fermentation has had a job offer.

I guess frustration can help. Certainly it's what compelled me to drive across America. I came back a different person from the lab rat I had been—a proponent of a simple 4-carbon molecule without a voice.

References

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Hunt VD (1981) The Gasohol Handbook. New York: Industrial Press.

Koonin SE (2006) Getting serious about biofuels. Science 311 435.

[3]Pages 43–46.

Driving 10,000 miles cross-country without using a drop of gasoline, **DAVID RAMEY** arrived back in Ohio on August 17, 2005. Environmental scientist, agriculturalist, physicist, engineer and inventor, Ramey—founder and president of Environmental Energy, Inc. (EEI)—drove his unmodified 1992 Buick, using only butanol.

Ramey's butanol was produced by his own patented process, and for his pioneering efforts to bring this organically derived fuel to market, he was recognized as the "1996 Technologist of the Year" by the Ohio Academy of Science.

Ramey has physics and mathematics degrees from California State University, San Diego. During the past several years he has been a researcher and an inventor in microbiology through a DOE/STTR grant. Also, in collaboration with Dr. S.T. Yang at the Ohio State University's Chemical Engineering Department, he obtained a $1 million dollar grant through the USDA's SBIR program to research, develop and commercialize butanol fermentation.

Environmental Energy, Inc., is now ButylFuel LLC, which is building a prototype that will produce 50–100 gallons of butanol per week, in order to characterize the process for scale up. The first scale-up will be a pilot plant that will produce 2 million gallons of butanol per year.