Final Report

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Research

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"Production of Acetic Acid for CMA Deicer"

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Report to the Iowa Department of Transportation
concerning work conducted at The University of Iowa
on project HR-304 entitled
"Production of Acetic Acid for CMA Deicer"

by

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SUMMARY OF CONCLUSIONS

Production of Acetic Acid for CMA Deicer

A. Low cost substrates are available in high quantity in Iowa. The most important are clarifier starch, pericarp starch, and corn steep liquor, and should cost approximately one-half that of "pearl starch" or corn.

B. Several microbial alternatives to *Clostridium thermoaceticum* exist, especially several that can use both glucose and lactate. Three organisms in particular should be examined experimentally: *Acetobacterium woodii, Acetobacterium carbinolicum* and *Acetogenium kivui*. Both mono- and mixed cultures should be examined.

C. These organisms need to be thoroughly studied with lactate, glucose, corn steep liquor and hydrolyzed starches as substrates. Lactate, glucose and protein/amino acid consumption should be followed concurrently with acetic acid production.

D. Experimental data collected with *A. woodii* demonstrate:

1. Corn steep liquor (CSL) is originally inhibitory to *A. woodii*.
2. Cultures can be developed that are resistant to this inhibition.
3. CSL can apparently serve alone as a substrate for acetic acid production.
4. Further careful, full time, experimentation will be needed to fully describe the potential of this organisms and similar others to produce acetic acid from CSL.

E. Corn steep liquor itself needs to be examined from two different perspectives:

1. Can CSL be centrifuged to remove the particulate material (e.g. bacterial cells and insoluble ppt), leaving a liquid that is richer in lactic acid, and lower in protein? This would be preferred, perhaps, since CSL has an excessively high N content for acetic acid production. Also, some components that are inhibitory may also be removed. The resulting "sludge" could be added to animal feed, as is currently done with entire CSL. The liquid stream could then be converted to acetic acid.
2. Can CSL be used directly or indirectly as a chemical feedstock for a "road salt" substitute? For example, CaMg lactate could be produced, due to the high lactate content (26% of dry weight) of CSL. If this was less corrosive than NaCl, it would certainly be cheaper than CaMg acetate. To evaluate this possibility, some process engineering and corrosion experiments are needed. In addition to these studies, some evaluation of the environmental impact should be made - e.g., since CSL is fairly high in N, run-off of N to the roadside should occur. Besides making the grass grow better, what would result? Due to the low SO_4 content, we would not predict that sulfide odors would be a problem due to microbial sulfate reduction.

F. A multidisciplinary approach using expert system technology can be of value in decisions regarding the economic viability of CMA production, when more experimental data become available.

SUBREPORT I: Evaluation of the Production of Acetic Acid from Midwestern Agricultural Products*

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I. INTRODUCTION

Although the overall objective for undertaking this project is to help decide on the best way to produce CMA, the tasks to be performed deal primarily with acetic acid itself. The objectives of our part of this project can be restated here:

A. Evaluate the cost and composition of potential low-cost fermentation substrates that are available in large quantity at central locations in Iowa.

B. Compare the nutritional and physiological properties of a variety of homoacetogenic bacteria relative to acetic acid production, based on information available in the literature.

C. Using both of these pools of information, evaluate the possibilities for use of substrates for acetic acid production that are significantly cheaper than the previous sugar, starch hydrolysate or whole corn based studies; also, compare the different acetogens encountered with the most commonly discussed acetogen, *Clostridium thermoaceticum*; arrive at conclusions on 1-3 of the best agriculture-derived substrates that should be further examined, and on 1-3 of the best organisms to evaluate experimentally.

D. Collect experimental data at the tube and fermentor scale on 1-2 of the possibilities in C above.

E. Comment on our understanding of acetic acid production possibilities from our perspective as microbiologists, and provide all this above information to Paul Peterschmidt for him to consider for his portion of this report.

F. In addition, we would like to point out the possible advantage of examining the use of an agricultural by-product, corn steep liquor, as a direct, non-fermented feedstock for a non-acetic acid deicer.

II. COSTS AND COMPOSITION OF POTENTIAL LOW-COST FERMENTATION SUBSTRATES

We have collected information on the costs of potential substrates, since the SRI (Marynowski et al., 1984) report identified feedstock price as the most important factor in final CMA product price. With corn and glucose syrup, the substrate represented 50 and 66%, respectively, of the total cost of production. Table 1 lists the costs of these substrates, determined as indicated in the footnotes. Table 2 describes the composition of several of the most relevant substrates. The price of non-agricultural sources, such as paper, are given for comparison even though paper hydrolysis is more difficult than starch.

*The opinions, findings and conclusions expressed here are those of the authors and not necessarily those of the Highway Division of the Iowa Department of Transportation.

What is readily apparent from Table 1 is that there are 3 substrates that are markedly cheaper than those generally considered: clarifier starch, pericarp starch and cornsteep liquor. All these are available in large quantity at corn wet milling sites in Iowa, and are at approximately one-half the cost of normal "pearl" starch or whole corn. The composition of these components suggest they could be blended to provide a good medium for acetic acid production. The majority of the carbon for acetic acid could be provided by glucose derived from the starch and part could arise from both the lactic acid and protein in the cornsteep liquor. However, at this time there is virtually no consideration given in the literature to these latter possibilities. The protein in the cornsteep liquor could also be used as a nitrogen source for growing the bacterium, and other components could serve as sources for minor but essential nutrients such as sulfur, salts and trace elements

III. PHYSIOLOGICAL PROPERTIES OF HOMOACETOGENIC BACTERIA RELEVANT TO ACETIC ACID PRODUCTION

Table 3 summarizes our evaluation of the literature information on substrate utilization by acetogenic bacteria. What is particularly important is that several species can use both glucose (to be obtained from starch) and lactate (to be obtained from cornsteep liquor). Virtually no information is available in the literature on details of the microbiology or kinetics of lactate use by homoacetogens; most work has emphasized glucose or other sugars.

It is also worth noting that there are many reasonable alternatives to *Clostridium thermoaceticum*, by far the most heavily studied organism for acetic acid production.

Table 1. Costs of Various Potential Substrates

Materials	Approx. cost per kg dry wt useable material
whole corn (a)	8.0 cents
pearl starch (b)	8.3
glucose syrup (c)	18.0
corn gluten (d)	20.0
cane molasses (e)	14.0
whey (f)	7.5
clarifier starch (g)	3.3
pericarp starch (h)	4.0
cornsteep liquor (i)	4.4
mixed paper (j)	2.0
newpaper (j)	3.0

a - whole corn price @ $1.75/bu
b - Hubinger, 6.5-8.5 cents/lb
c - Hubinger, $7/100 lb, 42%
d - Cargill, $100/US ton; Penick & Ford, $100/ton
e - Protein Blenders, I.C.; assume 65% useable sugars (w/w)
f - Twin County Dairy, Kalona
g - Hubinger, 0.4x starch price, sometimes a little lower
h - Hubinger, as above with clarifier starch, but estimate a little more expensive to process
i - Hubinger, $40/US ton dry solids basis; 25% of total CSL; 29 tons available/day
j - City Carton Co., Iowa City.

Table 2. Composition of Potential Substrates [% of dry weight]

Material	Starch	Sugar	Protein/aa	Lactic	Other
whole corn	71	-a/	11	0	-
pearl starch	> 85%	< 5%	< 5%?	< 5%	-
glucose syrup	0	> 90%	-	0	-
corn gluten	23	-	22	-	-
molasses	0	65	6	0	-
whey	0	65	13	-	-
clarifier starch	> 85%	-	-	0?	-
pericarp starch	10-30%?	-	-	-	fiber
cornsteep liquor	-	2.5	47	26	-

a/ information not available.

Table 3. Substract Utilization by Homoacetogenic Bacteria

Organism	Substrates Used					Ref.
	glucose	fructose	xylose	lactate	ethanol	
Clostridium thermoaceticum	+	+	+	-	nd	a
Clostridium thermoauto-trophicum	+	+	+	-	-	a
Clostridium formico-aceticum	-	+	-	+	+	a
Clostridum aceticum	-	+	-	-	+	a
Clostridium magnum	+	+	+	-	-	b
Acetobacterium woodii	+	+	-	+	-	a
Acetobacterium carbinolicum	+	+	nd	+	+	c
Acetogenium kivui	+	+	nd	nd	-	a

nd=no report on whether or not this substrate is used for growth.
C. thermoautotrophicum was reported to use lactose by Wiegel et al. (1981), but no other acetogens are reported to use lactose.
a, Ljungdahl (1983); b, Schink (1984); c, Eichler & Schink (1984).

IV. EVALUATION OF FAVORABLE SUBSTRATE/ORGANISM PROCESSES

From all the above information, hydrolysed starch from the clarifier or pericarp should be investigated in combination with cornsteep liquor, using one or more of the following organisms either in mono-culture or possibly in co-culture: *Acetobacterium woodii, Acetobacterium carbinolicum*, and *Acetogenium kivui*. Co-cultures can sometimes utilize more total substrates and can also sometimes grow better than either organism alone.

V. EXPERIMENTAL DATA

We have obtained a culture of *Acetobacterium woodii* and are currently growing it at the tube, bottle and fermentor scale. We have conducted a variety of tube experiments. The results of our preliminary experiments are described in detail in the attached Appendix, entitled "An Experimental Study of Corn Steep Liquor as a substrate for Acetic Acid Production by *Acetobacterium woodii*".

VI. RECOVERY OF ACETIC ACID

Among the methods for recovery of acetic acid include distillation, solvent extraction, and cystallization. Recovery by simple distillation is not economically feasible. Alternative processes and approaches are available, such as extraction combined with azeotropic distillation, acidification-extraction, supercritical CO_2 extraction, melt crystalization, membrane separation, electrodialysis and others. The details of these processes and the economic aspects of alternative strategies for recovery of fermentation acids have been discussed by several workers (Phillips and Humphrey, 1983; Busche, 1985; Kertes and King, 1986; Nomura et al., 1988). Experimental work in some of these areas (e.g. solvent extraction and membrane/electrodialysis systems) are particularly relevant to the potential economic viability of any acetic acid production system.

VII. CONCLUSIONS/SUMMARY

A. Low cost substrates are available in high quantity in Iowa. The most important are clarifier starch, pericarp starch, and corn steep liquor, and should cost approximately one-half that of "pearl starch" or corn.

B. Several microbial alternatives to *Clostridium thermoaceticum* exist, especially several that can use both glucose and lactate. Three organisms in particular should be examined experimentally: *Acetobacterium woodii, Acetobacterium carbinolicum* and *Acetogenium kivui*. Both mono- and mixed cultures should be examined.

C. These organisms need to be thoroughly studied with lactate, glucose, corn steep liquor and hydrolyzed starches as substrates. Lactate, glucose and protein/amino acid consumption should be followed concurrently with acetic acid production.

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E. Corn steep liquor itself needs to be examined from two different perspectives:

1. Can CSL be centrifuged to remove the particulate material (e.g. bacterial cells and insoluble ppt), leaving a liquid that is richer in lactic acid, and lower in protein? This would be preferred, perhaps, since CSL has an excessively high N content for acetic acid production. Also, some components that are inhibitory may also be removed. The resulting "sludge" could be added to animal feed, as is currently done with entire CSL. The liquid stream could then be converted to acetic acid.
2. Can CSL be used directly or indirectly as a chemical feedstock for a "road salt" substitute? For example, CaMg lactate could be produced, due to the high lactate content (26% of dry weight) of CSL. If this was less corrosive than NaCl, it would certainly be cheaper than CaMg acetate. Direct reaction with Ca+Mg salts might yield an acceptable product, but more likely, the CSL could be centrifuged (as mentioned above) to remove insolubles (little lactate should be lost), and the supernatant used to ppt. with Ca-Mg salts. This would still allow significant amounts of CSL protein to be added to animal feeds. To evaluate this possibility, some process engineering and corrosion experiments are needed. It would be good for the IOWA DOT to examine this possibility, due to the vast amount of CSL in the state and the potential savings by direct production of a deicing solution or solid, rather than involving expensive fermentation processes. In addition to these studies, some evaluation of the environmental impact should be made - e.g., since CSL is fairly high in N, run-off of N to the roadside should occur. Besides making the grass grow better, what would result? Due to the low SO_4 content, we would not predict that sulfide odors would be a problem due to microbial sulfate reduction.

VIII. SUGGESTED FUTURE WORK

The first priority should be to examine CSL as a potential direct road deicer feedstock (probably after centrifugal clarification), rather than via fermentation to produce acetic acid, as described above. Such a project should involve corrosion evaluation, deicing properties and environmental impact. A minimum of 6 man months is recommended, with an approximate budget of about $30,000.

If direct CSL use is not clearly practical, the microbial production of acetic acid should be fully investigated in the laboratory, as described above. A minimum of one-man year of effort, with a total budget (without overhead) of about $50,000 is recommended. We would be glad to prepare a proposal to conduct such experimental work, and feel that our experimental base and personnel experience would be valuable in such a project. If the project were initiated by a laboratory unfamiliar with these organisms, 1-2 man-months of work would be needed to gain this base and experience.

It is our strong opinion that the support of a project of significantly less magnitude will be a waste of money. We also feel that the project should be conducted by engineers or scientists with active, on-going research projects.

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APPENDIX

An Experimental Study of Corn Steep Liquor as a Substrate for Acetic Acid Production by *Acetobacterium woodii*

INTRODUCTION

Currently, all acetic acid, expect food-grade acetic acid (vinegar) is produced by chemical processes based on fossil raw materials. In vinegar production, a two-step biological process is used, in which glucose is first fermented to ethanol by yeast and then the ethanol is converted to acetic acid by bacteria of the genus *Acetobacter*. The theoretical maximum yield of acetic acid from this process is 67% on a weight basis (Sinsky, 1983). In recent years, production of acetic acid from renewable biomass using the homoacetogenic bacteria has been studied by several workers as an alternative to the above processes. The advantage of using these groups of organisms is that quantitative conversion of sugars to acetic acid with a 100% yield (on a weight:weight basis) is theoretically possible (Sugaya et al., 1986). However, in practice, maximum acetic acid yields are reported to be often in the range of 80-85% (Sugaya et al., 1986). This low productivity has been mainly attributed to end-product and low pH intolerance of the homoacetogens, as well as to the lack of efficient product recovery processes (Baronfsky et al., 1984; Schwartz and Keller, 1982; Wang and Wang, 1984; Terracciano et al., 1987; Weimer, 1987). In order to improve acetic acid production by this process, effort is now directed towards development of strains with more tolerance to high levels of acetic acid and low pH conditions (Schwartz and Keller, 1982; Reed et al., 1987).

In the effort to develop an economical acetic acid production method using homoacetogens, most studies have focused on *Clostridium thermoaceticum*, with glucose (as hydrolyzed corn starch) serving as the substrate. Very little work has been done to examine the process by using other homoacetogenic bacteria or other substrates. The use of alternative inexpensive raw materials would be a helpful factor since the cost advantage of the substrate could make the process more economical.

We evaluated alternative biomass feedstocks available in Iowa in order to identify potential substrates cheaper than glucose and conducted experiments on the utilization of the selected substrate by homoacetogens. Corn-steep-liquor (CSL) is among three substrates that are at approximately one-half the cost of the normal "pearl" starch or whole corn and which are available in large quantities at corn wet milling sites in Iowa. Also, the composition of CSL includes up to 26% lactate, a substrate known to be used by at least three homoacetogens (Ljungdahl, 1983; Eichler and Schink, 1984). Here we report the results from our initial experiments on acetic acid production from CSL using *Acetobacterium woodii*, a homoacetogen which can use glucose, fructose or lactate as a substrate.

MATERIALS AND METHODS

Organism. *Acetobacterium woodii* (Balch et al., 1977) was obtained from Dr. R. S. Wolfe.

Medium and Culture Conditions. Growth of cells and medium preparation were carried out by using the anaerobic procedures described previously (Balch and Wolfe, 1976; Daniels et al., 1986). The medium consisted of the following components (mM) in distilled water: KH_2PO_4 (2.94), K_2HPO_4 (2.3), NH_4Cl (5.6), $MgCl_2 \cdot 6H_2O$ (0.31), $CaCl_2 \cdot 2H_2O$ (0.27), $NaHCO_3$ (23.8), sodium formate (2.94), resazurin (0.003), $Na_2S \cdot 9H_2O$ (1.0), cysteine hydrochloride (1.4); yeast extract (Difco Laboratories, Detroit, MI), at a concentration of 2 g per liter and 10 ml vitamin mix (Wolin et al., 1963) per liter were also added. A concentrated solution of trace elements was added to this medium to give the following final concentrations (μM): nitrilotriacetic acid (78.5), sodium selenate (0.2), sodium tungstate (0.2), $MnCl_2 \cdot 4H_2O$ (20), $FeCl_3 \cdot 6H_2O$ (18.4), $CaCl_2$ (4.5), $CoCl_2 \cdot 6H_2O$ (8.4), $ZnCl_2$ (7.3), $CuSO_4$ (3.1), $Na_2MoO_4 \cdot 2H_2O$ (2), $NiCl_2 \cdot 6H_2O$ (4.2), $AlK(SO_4)_2 \cdot 12H_2O$ (0.4), $Na_2B_4O_7 \cdot 10H_2O$ (0.5). The gas phase was N_2/CO_2 (80:20, vol./vol.) and the final pH was 7.0. Sterile, anaerobic glucose and corn steep liquor (Sigma Chemical Co., St. Louis, MO), at final concentrations as indicated in the results section, were added after the medium was autoclaved and cooled.

The experiments were carried out in serum tubes (no. 2048-00150; Bellco Glass, Inc., Vineland, NJ) containing 5 ml medium and sealed with rubber stoppers (no. 2048-11800; Bellco) and aluminum crimps (no. 224183; Wheaton Scientific). Inocula for the experiments were grown in 50 ml amounts in 250 ml serum bottles (no. 223950; Wheaton Scientific) sealed with no. 1 black stoppers and aluminum crimps (no. 224187, Wheaton). Inoculum size in the experiments was typically 10%. The cultures were incubated at 30°C without shaking. Culture turbidity was measured by absorbance at 600 nm with a Sepctronic 20 spectrophotometer or Perkin Elmer 552-A spectrophotometer. All data are the average from duplicate tubes.

Acetic acid assay. Acetate was determined by the acetate kinase method (Andreesen et al., 1970). Acetate kinase (250 u/mg) was purchased from Sigma Chemical Co., St. Louis, MO. The assay mixture contained the following components in a total volume of 0.5 ml: Tris HCl (pH 7.4), 50 mM; ATP, 10 mM; $MgCl_2 \cdot 6H_2O$, 10 mM; $NH_2OH \cdot HCl$ (neutralized), 0.5 M; acetate kinase, 99 μg; acetate, 0.05-1.5 μmole. The assay mixture was incubated for 1 hour at 37°C, after which the reaction was stopped by adding 0.5 ml of 10% tricholoracetic acid. The color was then developed by adding 2 ml of $FeCl_3$ solution (1.66% $FeCl_3 \cdot 6H_2O$ in 1 N HCl) and measured at 546 nm in a Shimadzu UV-160 spectrophotometer.

RESULTS AND DISCUSSION

As shown in Table 1, CSL is among the cheapest organic materials available from corn-based processes. As part of our study to evaluate the potential of using cheap Midwestern agricultural products as feedstocks for a microbiological process to produce acetic acid, we examined the effect of CSL on the homoacetogen, *A. woodii*.

Growth of *A. woodii* on glucose in the presence of either 0.1% or 0.5% CSL was studied using inoculum grown under two conditions: in a medium with glucose (0.5%) as the main substrate or in 0.5% glucose and 0.5% CSL medium. Fig. 1a shows the effect of CSL on growth when the glucose grown inoculum was used; CSL was inhibitory to growth, causing a lag period of up to 6 days when added at a concentration of 0.5%. The inhibitory effect was greatly reduced when the CSL plus glucose grown inoculum was used (Fig. 1b); no lag and 2 days lag were observed with the addition of 0.1% and 0.5% CSL, respectively. Slight growth was observed in medium with 0.5% CSL as the only substrate when inoculated with the glucose grown culture (Fig. 1a), and about 30% of maximal growth occurred when the glucose plus CSL grown inoculum was used (Fig. 1b).

Acetic acid production levels, pH and cell density in *A. woodii* cultures grown under nutrient conditions varied as in the experiments described above are presented in Table 4. The data from tubes inoculated with the glucose-grown culture show that acetic acid production during growth on glucose is higher in the presence of CSL; 14% and 37% greater acetate levels were observed in tubes with 0.1% and 0.5% CSL, respectively, compared to the amount in tubes with no CSL added. However, the same effect was not apparent when the glucose plus CSL-grown inoculum was used, with only a slight increase in acetate observed in the presence of 0.5% CSL; this is likely due to the presence of carry over (from the inoculum) CSL in the glucose alone tubes. It should also be noted that the data on acetate and growth levels presented here are from culture tubes under conditions without pH control. Acetic acid production by homoacetogens results in a drastic pH drop in the medium, creating unfavorable conditions for further growth.

The level of acetate in cultures grown on 0.5% CSL alone was about 37-45% of that in cultures grown on 0.5% glucose, consistent with the growth levels attained. The limited growth and acetate yield on 0.5% CSL alone may be due to depletion of utilizable substrate in the CSL provided. Lactate, known to comprise up to 26% of CSL, would be the major known substrate available and is estimated at about 0.1% in the amount of CSL added to these cultures. In order to determine the utilization of CSL to a significant extent, larger amounts of CSL would have to be added to bring the levels of estimated lactate (or other utilizable substrate) in the cultures to within the range of the amount of glucose normally used (i.e. 0.5%). However, increased inhibition of *A. woodii* will occur with higher CSL levels and inoculum cultures adapted to these levels will have to be developed for conducting such experiments; developing cultures tolerant to high concentrations of CSL should not be very difficult as evidenced by the data in Fig. 1.

Thus, the results described show that:

1. CSL is inhibitory to *A. woodii* and would likely inhibit other homoacetogens.

2. Cultures could be developed with tolerance to the inhibitory effect of CSL.

3. The data suggest that CSL alone may serve as a substrate for acetic acid production by homoacetogens.

Further studies will be needed in order to determine the full potential of CSL as a substrate for acetic acid production by *A. woodii*. We suggest that further work with *A. woodii* include the following experiments (some of these experiments are in progress due to our own interests and we will pursue them, depending on time and financial resources available):

1. Repeat the above experiments but using lactate in place of glucose.
2. Examine the effect of CSL at concentrations of 0.5-2% in the presence of 0.5% glucose with the aim of developing optimal culture conditions for growth and acetic acid production from CSL. The inocula for this experiment will be grown in 0.5% glucose plus 0.5%-2% CSL and transferred in this medium several times before use.
3. Growth and acetic acid production under pH controlled conditions on a fermentor scale in medium with 0.5% glucose and 0.5% - 2% CSL should be conducted along with the measurement of lactate and glucose levels during the fermentation. This experiment would provide details on the kinetics of CSL utilization and as well confirm our observations on CSL use from the tube scale experiments.

The production of acetic acid from CSL should also be studied with other homoacetogens, particularly the lactate utilizers, in a similar manner as with *A. woodii*. Hydrolyzed clarifier starch and pericarp starch, the other potential substrates available in Iowa at cheap cost, should also be examined with *A. woodii* and other homoacetogens.

One fermentor strategy that would be appropriate to try is as follows. Since CSL inhibits to some degree, clarified CSL, adjusted to a basic pH, could be used as both a way to maintain pH control as well as continuously feed the process, keeping the inhibitor concentration low.

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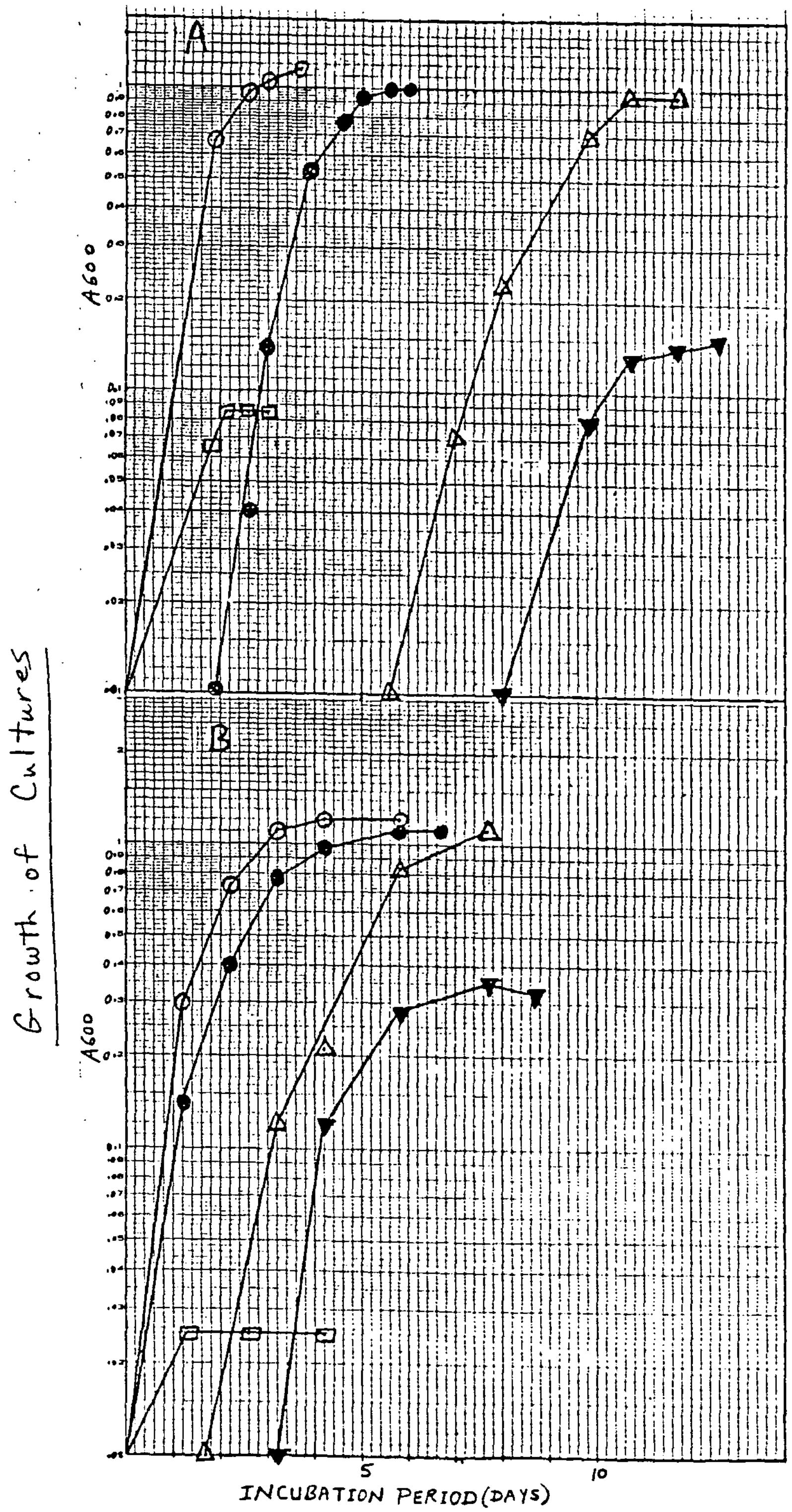
Table 4. Acetic acid production and growth in cultures of *A. woodii* grown on glucose in the presnece of CSL[a/]

Growth substrate	Inoculum grown on 0.5% glucose			Inoculum grown on 0.5% glucose + 0.5% CSL		
	mM Acetate	Final pH	Final OD600	mM Acetate	Final pH	Final OD600
0.5% Glucose	51	5.05	1.2	67	4.7	1.2
0.5% Glucose + 0.1% CSL	58	4.9	0.99	67	4.75	1.1
0.5% Glucose + 0.5% CSL	70	5.0	0.94	72	4.88	1.1
No added Glucose or CSL	-	-	0.08	-	-	0.03
0.5% CSL	23	6.4	0.15	25	6.37	0.33

a/ Corn steep liquor

FIGURE LEGEND

Fig. 1. Effect of corn steep liquor (CSL) on growth of *Acetobacterium woodii*. A, inoculum grown on 0.5% glucose; B, inoculum grown on 0.5% glucose + 0.5% CSL. Growth in medium with: O, 0.5 glucose; ●, 0.5% glucose + 0.1% CSL; Δ, 0.5% glucose + 0.5% CSL; ▼, 0.5% CSL and no added glucose; □, no added glucose or CSL.



SUBREPORT II: Report on "Economics and R & D prioritization as applied to CMA" by Paul Peterschmidt, Nancy Botten and James R. Buck

Attached, please find a copy of a summary of work on "Economics and R & D Prioritization" aspects of the project. More information on this subsection may be completed at a later date, due to the ill health of Paul Peterschmidt. In the interest of expediting the transfer of information provided in the accompanying subreport entitled "Evaluation of the Production of Acetic Acid from Midwestern Agricultural Products", we wish to submit both at this time. Our laboratory has now completed virtually all experimental and literature work, and further delay of communicating our results would not be advisable.

ECONOMICS AND R & D PRIORITIZATION: A MULTIDISCIPLINARY APPROACH USING EXPERT SYSTEM TECHNOLOGY

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ABSTRACT

This paper deals with the interaction of economic analysis and management through a multidisciplinary approach. The objective of the approach is to employ expert system technology to assist in management decision making regarding applications of funds to those projects and prospective products most likely to yield commercial rewards. Involved in this approach are industrial systems and methods analysis, market trends, reviews of actual and potential competitive costs and procedures, as well as other aspects of engineering economics. An example of the approach is shown involving new products from fractions of the corn wet milling industry, specifically, the importance of acetic acid in the production of calcium-magnesium-acetate (CMA) road deicer. Expert systems have been selected as an aid in identifying pathway priorities, to either help identify the more prospective pathways or at least help in overlooking the better prospects prior to economic evaluation.

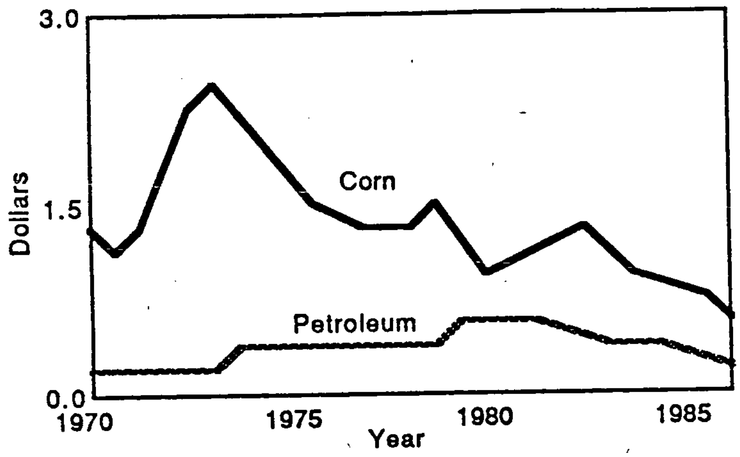
BACKGROUND

Considerable interest in CMA road deicer exists on the federal as well as the state (Iowa) level. The importance of acetic acid in the production of CMA road deicer is evidenced by the fact that it accounts for 75 to 85 percent of the cost of production; and if economic improvements are to be made in CMA production, a likely candidate to facilitate that improvement would be in the reduction of the cost of acetic acid. What is needed is to [4]:

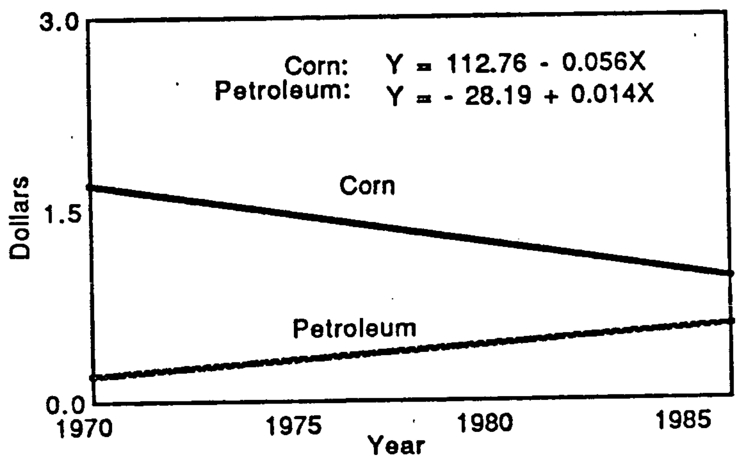
1. Identify the optimum bacterium for the fermentation process,
2. Predict the reproduction rates within the fermentation process,
3. Project these combinations into an "economy-of-scale" production facility and
4. Forecast selling prices.

The focus here is on the production of acetic acid, not the future of CMA. We do know that the cost of producing CMA is very high and this limits its marketability. We merely need to develop a procedure to identify the microorganism(s) and the fermentation pathway(s) which will allow CMA to be produced at its lowest cost.

Petroleum-based feedstocks, which are currently used are no longer considered economically viable; but corn - or the fractions of the corn wet milling industry - could represent an economically favorable alternative feedstock for the midwest. In other geographic areas such as New York more indigenous feedstocks such as whey and byproducts from the production of wine and fruit juices are utilized. Corn products are preferred over petroleum-based feedstocks as evidenced by the statistical fact that the cost per unit of production of corn is declining as compared to petroleum feedstocks which are increasing. These statistics taken over a fifteen year period are shown in Figure 1. Figure A represents the adjusted (for inflation) prices of corn and petroleum and Figure B their associated least squares fit [2] [3] [6]. It is evident by inspection that a break-even point should occur by 1991. Additionally, the finite character of petroleum fossil-based feedstocks is another driving economic force moving industrial processes toward the use of microbiology with corn and other renewable resources.



A: Adjusted Prices of Corn vs. Petroleum



B: LS Fit of Adjusted Price of Corn vs. Petroleum

Figure 1 Comparison of Corn and Petroleum Prices

It is evident that the problem of determining the most economic production of acetic acid from fermentation is multidisciplinary; therefore, the problem-solving approach is necessarily multidisciplinary. It requires expertise from the disciplines of microbiology, biochemistry (in particular, fermentation chemistry) and artificial intelligence (in particular, expert systems), chemical processing and engineering economy.

POLYMER CHEMISTRY

Polymer chemistry involves the study of chemical reactions in which monomers (molecules or compounds) are linked into repeating molecular structures called polymers, either compounds or mixtures. Hydrocarbons from the petroleum industry are examples of polymers that link carbon with hydrogen. A single chain results in methane, i.e., natural gas. Multiple chains in the methane series form other products such as ethane, propane, butane, and finally the paraffins. From these petrochemical polymers come many common products such as polyethylene, ethylene glycol, polyvinyl chloride, gasoline, naphtha, etc.

Chemical engineers who work with these petrochemical polymers break them down into smaller units and join them into new combinations working with relatively simple variables including heat, pressure and catalysts. In contrast, biochemical engineers must work with a wide variety of microorganisms and pathways, as well as many potential carbohydrate feedstocks. The polymer which is used for illustration is a polysaccharide, i.e., a complex carbohydrate such as starch that can be decomposed into monosaccharides, i.e., simple sugars such as glucose. The key differences between a "hydro - carbon" and a "carbo - hydrate" is that the latter contains oxygen, is comprised of a longer chain, and is subject to the tools of biotechnology. The problem is that the multiple research pathways of biotechnology requires some means of managing the resulting myriad of research alternatives. Expert systems are proposed as such a management tool (See "Expert System Technology").

In our example, the basic unit is the monomer glucose and the product is acetic acid, which will be reacted with calcium and magnesium to produce an organic road deicer salt, CMA. Inorganic salts have many disadvantages, including toxicity, corrosiveness, interference with plant growth, pollution of ground waters and streams and spalling of bridge decks. Organic salts overcome these disadvantages, but they are very expensive. A primary objective of this study is to bring down the cost of producing acetic acid, thereby reducing the cost of CMA. Acetic acid can be made from a petroleum hydrocarbon (propane) by applying heat, pressure and catalysts. An alternative production method for acetic acid involves renewable resources, namely starches from grains or other biomass, of which corn is one of the more abundant. The method generally is to unravel the corn polymer and then to convert it into acetic acid through a series of reactions using microorganisms.

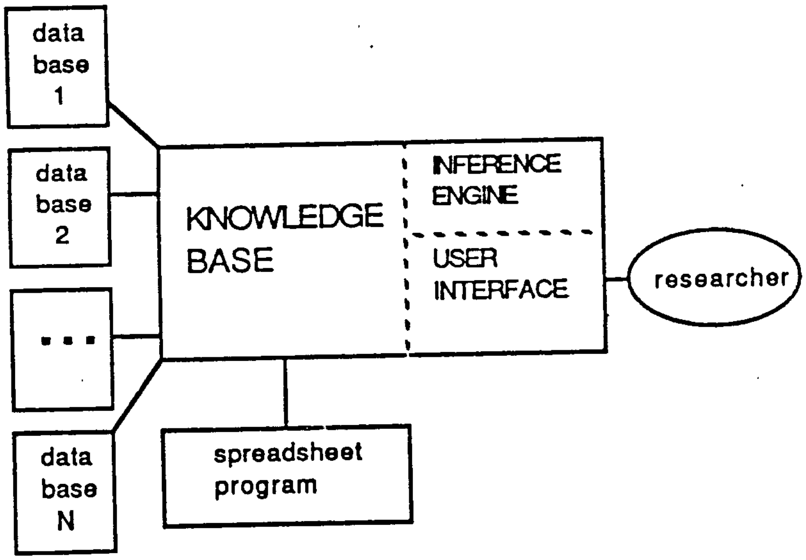
EXPERT SYSTEM TECHNOLOGY

Expert systems belong to the field of artificial intelligence which is concerned with the application of computers to tasks that require knowledge, perception, reasoning, understanding and cognitive abilities [1]. Expert systems are knowledge-based systems which make domain knowledge explicit and separate from the rest of the system. But, while virtually all expert systems are knowledge-based, the converse does not hold. An additional quality held by expert systems is that they apply expert knowledge to difficult real-world problems [5].

Structurally, an expert system contains three main subsystems [1]:

1) A knowledge base, which contains data and rules (or other representations) that use the data as the basis for making decisions;
2) The inference engine, which contains an interpreter (decides how to apply the rules to infer new knowledge) and a scheduler (decides the order in which rules should be applied); and
3) The user interface, which proves a language for communication between the user and the computer.

The structure of the expert system for our acetic acid illustration is shown in Figure 2. Aside from the three main subsystems, i.e., the knowledge base, inference engine and user interface, there are two key structures, multiple data bases and a spreadsheet program. It is likely that a commercial shell program will provide the inference engine and at least part of the user interface.



data bases (not all inclusive):
1. strains of microorganisms
2. resultant fermentation products
3. microorganism performance
4. competitive feedstocks
5. process systems
6. material balances
7. capital investment requirements
8. number of new technologies required
9. market statistics
10. market logistics
11. geographic customers
12. logistical economics

Figure 2 Acetic Acid Expert System Structure

Heuristics are methods of problem-solving which use rules of thumb to limit the solution search space, but do not necessarily lead to an optimal solution. Although an algorithmic method does guarantee an optimal solution every time, a good heuristic method should produce an acceptable solution most of the time. Unfortunately, algorithmic methods are limited by a "combinatorial explosion." The application of biotechnology research to corn refining is one in which there are literally thousands of strains of microorganisms. The numerous strains, coupled with hundreds of process pathways, create many variants which results in a combinatorial problem in defining R & D opportunities. Management of this problem is the driving force for the use of expert system technology.

Therefore, the knowledge base for the prioritization of acetic acid research programs consists largely of heuristic guides relating to the economic principles important to R & D management. In addition to judgement factors, empirical data are imported from the data bases. Some data bases exist and can be accessed by the expert system in their current form, while other data bases must be created. The expert system uses the heuristics and empirical data to prune and search basic research avenues for the identification and prioritization of those that hold a premium position for commercial development. Finally, the data are analyzed using spread sheet software accessible from the expert system to provide a "best estimate" of the production economics associated with the more preferred pathways.

MANAGING R & D THROUGH ECONOMIC ANALYSIS

What follows are the economic heuristic guides for selection of the most advantageous microbes, microbial pathways and feedstocks for production of acetic acid. These reflect current expertise relating to the general principles used in R & D discovery and prioritization. These principles, when coded into the knowledge base of an expert system with a value reflecting their relative importance, are combined with empirical data about the microbes, pathways and feedstocks in the form of data bases. The most economically favorable alternatives are a product of the interaction between the empirical data and the heuristic guides. The recommendations are then reported with values reflecting the relative potential of the alternatives. These are the key economic heuristic guides:

Functional Fixedness - People often are apt to think of the traditional uses of objects or traditional ways to make products. An effort should be made to escape from functional fixedness in favor of innovative uses and methods.

Identify Property Gaps - In existing or potential products, there are shortfalls between desired and existing properties. In existing products these shortfalls are competitive opportunities. In potential products these shortfalls are R & D opportunities. In our illustration, an example would be the shortfall represented by the undesirable qualities of inorganic salts (toxicity, corrosiveness, environmental impacts, etc.)

Track Technologies Forward And Backward - In order to find the pathways to new products or processes, new emerging and partially mature technologies (e.g., biotechnology) should be tracked and reviewed as a forward vantage point. Also historical antecedents should be tracked toward the reasons for past changes against contemporary changes and possible modifications with newer technologies as an "If we knew then what we know now . . ." appproach. For example, it is very important in our illustration to understand the price history of propane since it is one of the feedstocks currently used in the production of acetic acid and because the price history probably follows closely to that of petroleum.

Needs-Volume Analysis - Products spring from human needs and product quantities are determined from the quantities of potential sales as a driving force toward prioritization. The pathway from potential buyer to the fundamental products needs to be assessed as those projected volumes should constrain or expand the potential R & D investments. For example, a data base is needed for potential buyers of products in a regional market because of the high cost of transporting CMA. Associated problems are break-evens between transportation costs and scale.

R & D Uncertainties - After the gaps are identified, those gaps need to be evaluated as to their economic potential. In this evaluation, the longer the gaps in terms of needed technology developments to close the gap, the greater the uncertainties of doing so and the lower the probability of success. For example, various microorganism properties such as reproduction rates may be unknown. Those avenues would need to be identified as of greater risk.

Parametric Costing - Products and processes have components as cost centers and processing characteristics associated within these components as parameters. Those parameters associated with the greatest costs are prime candidates (opportunities) for R & D activities. In early R & D stages, this principle aids in identifying R & D priorities. In R & D stages, the relationships between parameters and costs provide a basis for design refinements in the classical Economic Principle that "marginal costs should be balanced across all components of a product or process." In our illustration, parametric costing needs to be made for the fermentation processes which can change geographically with potential customers and feedstock quantities. Thus, with information from these data bases and the parametric costs, various fermentation plants can be approximated in the regional economics.

Identify Competitors - Current needs are met with potential competitiors of new products and processes. Success in R & D depends on beating the competition, so the competitors must be identified and tracked historically. Changing prices of the competition(s) inputs to production signal the potential timing of the "window of opportunity;" and the sooner the window, the greater the economic potential and the greater the R & D priority. This principle is anlogous to the time value of money.

Differentiate From The Competition - Every product is a bundle of properties (attributes) toward those desired by potential buyers. The success of an emerging new product in the marketplace or a new process depends upon being different from the available competitiors in price, quality, or effectiveness. For example, organic salts are superior to inorganic salts in terms of environmental impact and other qualities (corrosiveness, etc.) In processes, "flexibility to meet demand changes" is another important property in today's economic environment.

The Economics Aren't Always Where Expected - Be alert to advantages which new technologies posses because sometimes what appears to be a minor advantage can solve an unexpected difficulty. At the same time, the number of new technologies should be kept at the smallest number necessary - perhaps two or three - since immature technologies often require additional basic research and / or the development of special tools or methods. One set of advantages is the wastes which can be turned into new coproducts. An example from our illustration involves an economic effect that develops by removing (by solubilizing) the extra starch from corn gluten feed and using it for acetic acid production, which increases the protein percentage by weight of the feed. There is no recognition by the market of the starch contained in the gluten feed since it is sold primarily on the basis of its protein content. The result is an enhancement of the market qualities and potential price yield of the feed while at the same time producing a valuable feedstock.

OVERALL APPROACH

It is helpful to first examine the list of characters as shown in Figure 3. The corn growers need to enhance sales to reduce current overproduction. If new products from wet milling can be made through fermentation, this opportunity will increase the sales of corn and the value added in wet milling. To the fermenter operations, there are the coproducts that add economic advantage to cattle feedstocks (higher protein corn gluten feed). The new potential market of CMA via acetic acid provides an enhanced quality product for sales where the economics are improved by optimization of the acetic acid fermentation process, which provides a coproduct to help meet petrochemical competition. Since each fermenter has expensive shipping costs of products and feedstock limitations, the markets would appear to be regional.

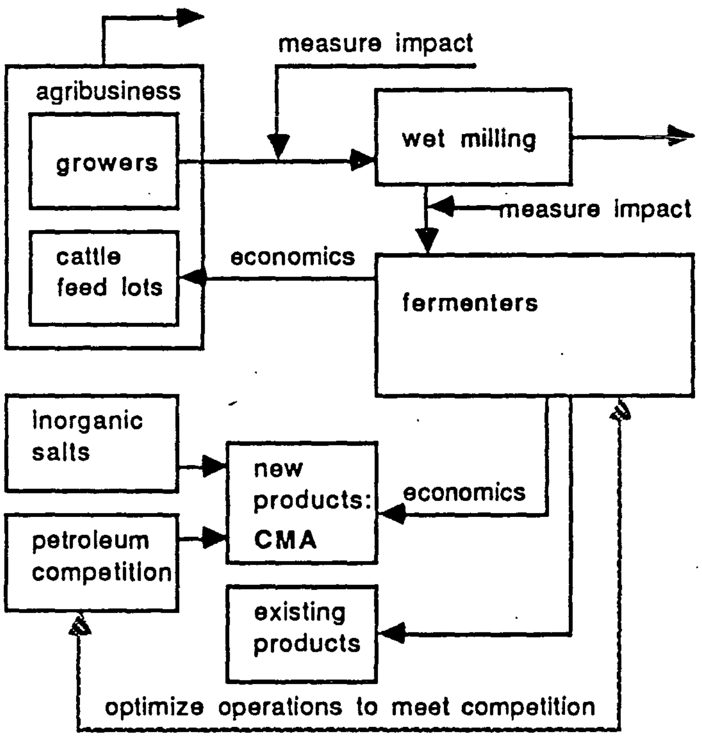


Figure 3 List of Characters

Management of the prioritization and selection of optimal acetic acid research scenarios requires the performance of the following tasks in this approximate order (Note that tasks #2 through #5 involve the expert system approach):

Task #1 Study the history of acetic acid including its commercial production methods, markets, end products, growth trends, etc. Determine the present state of the art including feedstocks, production methods and costs, energy components, selling price, markets, etc.

Task #2 Identify variables for measuring the practicality of commercialization. Some of the heuristics above relate to those variables. Once identified, these variables need to be converted into weighted rules for the expert system.

Task #3 For existing uncertainties, those that can be evaluated from lab experiments need to be identified. Additionally, some measure of the time and cost of this lab work needs to be established or estimated.

Task #4 Build a regional economic market and source model for sizing and locating the fermentation plants - to assess the economic viability and logistical economics - with districts made up of multiple regions.

Task #5 Empirically define the material balances. Prepare projections which provide an estimated production capital cost figure. Analyze the data using spreadsheet software accessed from the expert system to provide a "best estimate" of the production economics associated with the preferred pathway.

FINAL REMARKS

What this paper has attempted to show is how using engineering economics and an expert system with multidisciplinary data bases can assist management in decision making in an R & D function. Neither tool alone can accomplish what is necessary to discover and prioritize the research projects and products that are most likely to yield commercial rewards, but together they can minimize the complexities of biotechnical research.

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ACKNOWLEDGEMENT

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