Published by The Internet-First University Press

William J. Jewell:

Reflections on an Academic and Commercial Career

William Jewell, Professor Emeritus in Biological and Environmental Engineering at Cornell University, traces the arc of his professorial career as a teacher and researcher. His early interests in environmental issues, under-girded by his early interests in utilizing higher plants as a remediation tool, led him to some unique areas of research and teaching interests. He was one of the early explorers of how to blend his academic interests in environmental and ecological engineering with an entrepreneurial direction. He reflects upon the joys and miseries associated with his pioneering work that straddles the two distinctly different cultures of academia and the world of commerce.

Cornell University
Version: February 2015

This book – http://hdl.handle.net/1813/38201
Books and Articles Collection – http://ecommons.library.cornell.edu/handle/1813/63
The Internet-First University Press – http://ecommons.library.cornell.edu/handle/1813/62

An Incremental Book

About the Author

William J. Jewell

BS, Civil Engineering, University of Maine, 1963
MEng, Sanitary Engineering, Manhattan College, 1964
PhD, Environmental Engineering, Stanford University, 1968
Postdoctoral Fellow, University of London, Westfield College 1969
Professor of Biological and Environmental Engineering, Emeritus

Specialization: Environmental Engineering/Ecological Engineering

Dr. Jewell practices environmental engineering with a focus on micro- and macro-biological processes. Much of his teaching and research are in the areas of ecological engineering, natural system treatment and management of wastes, resource-recovery agricultural waste management, biotreatment of toxics, biological and chemical mechanisms involved in pollution control, energy conservation in waste treatment and renewable energy generation via anaerobic methane fermentation. These topics are incorporated in three courses that he taught: ecological engineering, human impact on the Earth, and pathogen management in animal wastes (in the College of Veterinary Medicine).

His research program included a large R&D effort to develop small scale anaerobic digesters that could be cost-effective on small farms. This led to construction of the largest biomass digester in the world in 1982 in Arizona via his private company, Microgen Corporation. Today many of the several hundred farm-scale operating systems in the U.S. use the design developed in this extensive R&D program.

The development of natural processes for pollution control led to wastewater treatment systems referred to as "Resource-Recovery Waste Management" that have the potential to recover energy and other valuable products. This work was recognized by the USDOE for a national award for "Energy Innovation-Contribution to the Nation's Energy Efficiency" in 1988.

Recently, the Resource-Recovery approach has been applied to dairy waste management. A system that completely converts 100% of dairy waste into useful products (energy, purified humus, and high protein feeds) has been piloted and is awaiting full-scale demonstration.

Jewell's research program has been characterized by innovations in areas such as microbial biofilm-applications, invention of the anaerobic composting process, and hydroponic plant applications. Biofilm treatment of chlorinated ethanes led to the first biological process capable of completely removing the most common groundwater contaminate and this work was recognized as one of the most important studies in chemistry in 1993

Publisher's Note

This book, and the companion oral history interview of Professor Jewell* (http://hdl.handle.net/1813/37006) by Professor Beth Ahner, portray the legacy of this faculty member whose pioneering efforts spanned several high priority national research issues during his active career. His research and teaching explored several broad areas of contemporary biological remediation—utilizing anaerobic digestion, biofilms, and other creative innovations. His early efforts in animal waste management quickly broadened from a focus on remediation to the simultaneous recovery of energy from these processes. He is widely known for his use, as resource recovery tools, both live plants (algae, cattails, duckweeds, etc.) and crop residues that are not sources of human food. Through an intense and passionate effort, Jewell and his students pioneered many techniques useful in dealing with environmental issues, exploring new energy sources, and clarifying sustainability issues. After trying to bring his inventions to the "real world" through collaboration with existing corporate entities, he eventually resorted to working through entrepreneurial structures that he and his colleagues created. He recounts the stresses associated with innovative research and simultaneously pioneering commercialization activities. He reflects upon the challenges of working within two very distinct cultural environments (academia and commerce) that have very different goals and rewards systems. His reflections also reveal how this research university is struggling to identify suitable protocols that enable its faculty to market their creations and patents for the broader public good, while at the same time not compromising the need for its faculty to consider issues of the broader public good impartially. In addition, faculty must not be compromised by conflicts of interests with respect to the public, the university, other faculty colleagues, or with staff and students. The IFUP believes that the reflections reported herein are worthy of thoughtful consideration by all of these groups.

The Internet-First University Press
December 2014

Copy editor and proofreader: Dianne Ferriss
Producer: J. Robert Cooke
Published by The Internet-First University Press, Ithaca, New York
Co-founders: J. Robert Cooke and Kenneth M. King
Online host: The Cornell University Library

* Contact the author: William J. Jewell, wjjewell@gmail.com

Preface

I began writing this summary of my career about three years ago at the urging of a friend and colleague, Professor Emeritus J. Robert Cooke. Bob and I shared a number of experiences in our careers, such as the challenges of trying to combine our professorial life with a commercial career. It was in this continuing sharing that he convinced me that my "story" should be told.

My career is one of magical highs and a few lows. I must admit to having a very idealistic view of life, maybe a Boy Scout attitude. Writing this material has been difficult in some ways because it forced me to face some of the negatives that were unexpected. Several editors helped me avoid the negative details that serve no purpose.

My background is one of humble beginnings in Maine. My family's love and caring eliminated all concerns that I came from a financially poor background. My brother and I were the first in our family to go to college [my brother also became a professor at the University of Wisconsin, Eau Claire]. From the time I set foot on a college campus until I finished my Post Doc in Europe I was on full scholarships. My scholarships were so generous that I was able to save enough money to buy a sports car [a beloved TR-3] late in my undergrad years.

The single most influential person who set me on my career path as an environmental engineer was Professor Otis J. Sproul at the University of Maine [who retired in 1995 as a Dean of Engineering at the University of New Hampshire]. My first summer research project was in Prof. Sproul's lab and my first consulting job was with him. Perhaps this is where I learned the importance of getting into the field and getting dirty in order to actually understand the problems we face in the environment. However, I did not need to start with running 24-hour waste collection samples at a rural tannery – one of the smelliest and dirtiest jobs one could imagine – as my first consulting job! Thanks Prof. Sproul!

Many other people shaped my career and should be acknowledged here. At Manhattan College – Donald J. O'Connor, Wes Eckenfelder, John Jeris, and a number of Christian Brothers and Father Tausig; and at Stanford University my mentor and inspiration, Professor Perry L. McCarty, and a full-time research technician with whom I was privileged to work, Mrs. Victoria Mongird.

My class at Stanford was one of the earlier graduate classes in Environmental Engineering and one of the most close-knit groups. For over three years we lived, argued, influenced each other, and partied together – James T. O'Rouke [deceased], James Young, and Pat Atkins.

My Postdoctoral study in England launched me onto my career in many amazing ways. I split my time from May of 1968 to August 1969 between London and Stevenage – at the University of London's Westfield College and at Europe's foremost government facility, The Water Pollution Research Laboratory. One person and his family made the 15 months I spent there the best experience: Peter Maris, along with his family who became my family [Patricia and children who became our God Children – Timothy, Ian, and Louise]. If my career is judged successful, it is partly due to the loving care that my eventual wife and I received from the Maris family. Others at the lab who made this a wondrous experience were: Morlais Owens, Reg Bailey, Bert Rolley, and the lab director Tony Downing. My mentor at the University of London was a world famous algologist, Professor G.E. Fogg. Professor Fogg took me under his wing and included me in the storybook life of a famous English Professor. Professor Fogg was inducted into The Royal Society. During my stay there my wife and I were included in parties at his house and at the Chancellor's house. We were married during this year at St. Nicholas Anglican Church in Stevenage [built in 1025!]. Peter and Pat Maris stood at our wedding and Professor Fogg was the stand in for Marlene's father.

Thanks to introductions by the team at the Water Research Centre and to Professor Fogg, I spent the summer of 1969 touring many of continental Europe's water research stations and met many of the world's leading scientists – many of whom remained close colleagues and friends throughout my career.

Stanford University spoiled me forever in the academic realm. I always said that living in such a boring weather climate as Palo Alto, where the sun came up and never was shaded by even a little cloud for over seven months a year, was most difficult to take for a student from Maine! But the academic environment of Stanford was so rich in great research and teaching that it provided a background very difficult to find at any other institution.

During my career, my students and I were fortunate to solve some of the most difficult and challenging environmental and energy problems facing the world today. These included: quantifying energy consumption in food production and showing that "energy-independent food production" is possible via retrieval of renewable energy from waste generated on farms. This work resulted in the important concept of "energy-independent farms." New anaerobic processes were discovered, including the most advanced form of biofilms and "anaerobic composting." We paved the way to show that concentrated human wastes could be pasteurized without adding any external heat energy and toxic metals could be removed and recovered from such wastes. Later we showed that combining energy recovery with natural soil and plant processes could not only produce clean energy, but all other materials could be converted into useful products – such as flowers and food – while converting sewage to drinking water quality. These process combinations resulted in systems we referred to as "Resource-Recovery" applications. Ultimate applications should result in "sewage treatment parks, Energy-Independent, and Pollution-Free Farms."

My interest in natural processes began with the modeling of algae in flowing streams at Manhattan College, and continued with defining what happens to algae in natural systems for my Ph.D. These experiences led me to contribute to Ecological Engineering. I describe Ecological Engineering as the language of sustainability. Today, my models of natural processes can predict not only what happens to most pollutants in soils and plants, but we can also predict the size of a wetland necessary to produce drinking water from wastes, plant yields in such systems, how deep the sediment will be any time in the future, and nutrient composition of resulting sediment. All of these models started with my M.E. at Manhattan College and my Ph.D. dissertation at Stanford. This demonstrated a pretty nice long shelf life of a Ph.D.!

Early in my career the term "Ecology", Rachel Carson's work, and understanding of natural processes was in the early stages of impacts and understanding. In fact, there was a raging argument that came close to name calling in professional literature over whether chemical processes or biological processes were superior approaches to waste control. As this rather embarrassing argument was coming to a close, one perpetrated and supported by engineers at Penn State and Berkeley over the use of natural systems became the next big argument.

Most Environmental Engineers were stuck in the past and had little knowledge of alternative biological treatments, such as constructed wetlands. In my efforts to understand how natural systems could be used, it became crystal clear that these systems were superior in many ways to most conventional approaches. While considering the impact of natural systems for purification, I began to look at the "bigger picture" and the impact of renewable energy on our world. This led me to believe that anaerobic systems used in "Bio Refineries" would have a prominent role in our future. And this gradually changing philosophy has shaped my career.

Early in my career I came to understand the potential of saving billions of dollars worth of energy by switching to anaerobic processes. Not only could we save communities huge amounts of money, but also energy production would result in generating billions of dollars worth of renewable energy. The problem was "conventional wisdom" - "anaerobic biological systems" were "known" not to be capable of purifying sewage. These microorganisms do not work either in dilute and/or cold organics like sewage – two barriers thought to be sacred – or so it was assumed.

But my new biofilm process seemed to be able to challenge this long-held "wisdom." So I suggested that my first Ph.D. student, Michael Switzenbaum, define lower limits to methane production with my anaerobic biofilm process. His work and several more Ph.D. dissertations proved that not only could they function down to near freezing, but they also could be as efficient as conventional systems. Voilá, energy producing sewage treatment processes. This successful research led me on a lifetime effort to convince others via research, teaching, and commercialization that waste treatment could result in energy generation with many other side benefits.

My commercial efforts began with my best friend, and three-year roommate, at the University of Maine, S. William Ireland who became my partner in JI Associates, Inc. While I remained on a nine-month contract at Cornell University, Bill worked full time for JI Associates. Our first office was in the beautiful ocean-side community of Ogunquit, Maine, in the Colonial Inn, one of Bill's father's hotels. This continued for several years until it was clear that the hurdles we were facing in innovative technology commercialization were not going to lead to significant cash flows, at least in the near future. So I recommended that we dissolve JI Associates and switch our attention to other methods of raising funds. It was not until Bill's early death from cancer that he confessed that he never dissolved JI Associates and had hoped we would pick up where we left off after my retirement from Cornell.

I was convinced that innovative technology commercialization was not only part of my life's mission, but that it would make me a better professor. I never envisioned leaving academia completely, but I also felt that a close tie between the highest levels of academia and commercial worlds was the optimum career. So Microgen Corporation was established as a traditional Delaware-based corporation in the early 1980s and continued until after 2000.

Many people should be acknowledged for their interactions with Microgen, both positive and negative. Besides my early partner and best friend, Bill Ireland, William T. Flukinger experienced many of the roller-coaster effects of Microgen throughout the latter part of his career. While working full time for DuPont, Bill became convinced that Microgen's mission and my work deserved to be transformed into benefits for society. After straddling DuPont and Microgen for several years, Bill Flukinger took early retirement from DuPont and worked full time for Microgen – at no salary! It was Bill F.'s support, friendship, and great good humor that supported me in our continuing frustrated efforts to make Microgen and my technologies successful in the "real world."Some of his story is also included here.

Microgen was used to conquer a number of major hurdles. It was one heck of a ride for over two decades. But it never was the success that I expected. A large part of this story relates some of the successes and challenges that I faced trying to run Microgen.

The final part of this career description was generated solely because Bob Cooke said that the most important part would be for others to see the lessons I learned from my commercial experience.

I would be completely remiss if I did not mention my partner and best friend, and wife, J. Marlene [Bryan] Jewell. It is impossible to attribute all of the support and reasons why Marlene was key to my career, but without her much of it would not have been possible. She went on this ride with little choice, "for better or worse," and the many 100+ hour workweeks were challenging in many ways. Description of this important part of my career is largely missing from this document.

One story should frame Marlene's role in my career – both good and bad. She always kept me grounded and humble in the face of the Earth's very challenging problems on which I worked. At a conference I helped to organize in Venice, Italy, as we were walking along the canal, I noticed a couple walking towards us. I whispered to Marlene that this couple was attending the conference and we should stop and chat. As we introduced ourselves the older gentleman, who was from South Africa, took a step backwards and said: "Bill Jewell, … pause … not The Bill Jewell," and after another pause he said louder, "Not THE BILL JEWELL!" After accepting his compliment and later back at our room, Marlene said, "Don't get too big a head over that guy and his invitation of a complete expense paid trip to South Africa. You still must stick to your commitment not to participate in anything there until apartheid is eliminated!"

At times my team of full time researchers at Cornell approached the same number of faculty in the department. I hope descriptions of multiple successes reflect that most contributions were made as a team effort. A significant foundation for our successes was due to several amazing office professionals who supported my team and me. They included Claudia Ellis, Diane Harbert, Lois Brown, and Sue Fredenburg. Their welcoming smiles over almost four decades everyday I entered my office, and their attempts to keep me out of trouble continue to warm my heart to this day.

Finally, I should say that for someone who has written thousands of pages of technical reports and hundreds of reviewed articles, this has been difficult to translate my 40-year career into something that may be worth reading. I never liked "tooting" my own horn. Keeping my resume up to date was always a challenge. In fact, when I looked for one of the first products of my career to reference here, I could not find it – I never listed it in my resume. It was the publication of the first national conference on rural environmental engineering that I organized in 1972 while at the University of Vermont. Bob Cooke knows this difficulty of mine first hand, as it was his patient but persistent nudging that has resulted in this description of my career.

I would like to thank Bob Cooke for his long-term encouragement to complete this written summary of my career, and for his friendship. Bob has been the key person in enabling many aspects of Cornell University's history to be recorded for posterity, he has made significant contributions to worldwide electronic publishing, and I have been humbled to be included in his wide scope of efforts. I also thank Darcy Brason-Lediett for his early editing and Dianne Ferriss for final editing of the text.

WJJ
December 2014

Contents

I. Education, Early Work Experiences, and Teaching

I. A. Overview

Looking back at a wonderful childhood and high school in Maine, nine years of college education at seven different colleges, and over 40 years of college teaching and research, it seems a little like a fairy tale.

Since most of this overview deals with my professional career, I limited most of my comments to that aspect of my career, beginning with postdoctoral research (post-doc) spent jointly at the University of London (Westfield College) and the British government's Research and Development (R&D) Water Research Center.

Teaching appointments were at vastly different institutions: first, at the University of Texas, Austin, followed by the University of Vermont, then at the great Cornell University.

Timing and societal problems were such that significant research funding was available to me for much of my career. Total outside funding of projects that I initiated came to around $13 million. Although renewable energy and rural pollution control support nearly disappeared for about a decade beginning in the mid-'90s, I had accumulated enough resources that I was able to continue laboratory research with little or no financial support until the end of my active career in 2008.

My teaching and research areas were characterized by attempts to address more pressing problems of the rural environment. My approach was to ask the questions:

- "What barrier prevents solution of a major environmental or energy problem?" and
- "Do I have the potential resources to attack that barrier successfully?"

My two-hundred-plus publications reflect exciting experiences in many areas and, I believe, made a significant contribution to understanding pollution, energy, and agriculture. Most focused on:

- Anaerobic digestion fundamentals, biofilms, and innovative biological process creation;
- rural environmental engineering;
- interaction of energy and agriculture;
- ecological engineering processes and systems; and
- toxics bioremediation.

I. A. 1. Recognitions

Honors include a National award in Washington, D.C., from the Secretary of the U.S. Department of Energy for innovative contributions to our Nation's energy needs, and a similar tribute from the Governor of New York.

Our work became the focus of one of the *New York Times'* science writers,[1] and in one Sunday *Times,* my interest in developing natural sewage treatment processes using higher plants covered two full pages – including the front page.

My work was also featured on a Nova-like program, "Beyond Tomorrow," produced by Australian television and shown in over 75 countries. I will never forget the 14-hour day spent filming all over Ithaca for the 20-minute television spot.

The American Chemical Society each year chooses a few projects to promote in a widely distributed colorful brochure. One year, my toxics bioremediation work was chosen as one of the five most interesting and promising research projects in the country. I was also a nominee for some of the most prestigious honors in the country, including: Nominee for Tyler Prize for contributions to protecting the environment and developing new sources of energy, Charles Valentine Riley Award for innovative improvements to American agriculture and health of the environment, Alexander von Humboldt Award for most important five-year research contribution to agriculture.

The publication of which I am most proud, however, is a technical summary of 15 years of R&D on resource-recovery waste management published in the *American Scientist* magazine.[2] Other bits and pieces of my work have appeared in *Popular Science* magazine, *Readers Digest*, and other publications.

I. A. 2. Thoughts on Teaching at Cornell

Personal interactions with my students were the highlights of much of my work. I was told that I had the third-most-total graduate students in what is now the Department of Biological and Environmental Engineering. Today my Ph.D. students are professors in New Jersey, Connecticut, California, Michigan, Oklahoma, Utah, Mexico, Denmark, and the Netherlands.

1. Jane E. Brody, "Sewage Project Could Turn Waste Into Profits." *The New York Times*, Sec. C of Science Times (November 3, 1987): C1-C4.

2. W. J. Jewell, "Sewage Treatment" Parks, *Washington Post* Magazine (February 1994): 189-95. W. J. Jewell, "Resource-Recovery Wastewater Treatment, *American Scientist* 82 (July-August 1994): 366-75.

I can single out each student with my favorite times and experiences, but one in particular, Dr. Gosse Schraa [Fig. 1], spent more time with me than any other student. Gosse did his undergraduate work and Masters at Wageningen University in the Netherlands where their program included an externship. He decided to come to the States to pursue his undergrad externship experience with me. Gosse returned to the Netherlands to complete his bachelors and masters degrees, and shortly after, he applied for a Ph.D. degree with me.

Gosse is presently a Professor at the number-one agricultural university in Europe, Wageningen University, The Netherlands. A few years ago, he received one of the greatest honors that a teacher can receive – his university students voted him the best professor at the University covering a period of five years.

Figure 1. Professor Gosse Schraa analyzing groundwater samples from land treatment of food processing wastes. This was part of Gosse's undergrad externship during his senior year at Wageningen University, Netherlands.

The American university teaching approach is still baffling to me. Generally, there is an expectation that engineers and scientists will automatically be good teachers once they receive advanced degrees. For the most part, they are not good teachers. Institutions must give them time, opportunity, and the resources to become good or even great teachers. Fortunately, the institutions at which I worked recognized this and strongly encouraged professors, especially new assistant professors, to participate in teaching seminars, retreats, and courses.

About mid-career, my teaching methodology transitioned from a lecture-based format to a dynamic teaching style, with more student interaction. At a teaching seminar sponsored by my college (Agriculture and Life Sciences), a famous teaching innovator presented the following example of how poor the lecture-only format is at transferring information. He informed his audience of over 300 faculty that he was going to conduct an experiment (during his presentation) that would challenge the lecture format. At some point he was going to raise his right hand and hold it there. When he did that, he wanted everyone in the audience to do the same.

About fifteen minutes into his presentation, he raised his hand. I expected an instantaneous response from the powerful Cornell faculty. I raised mine and looked around the auditorium – less than a fifth of the audience had raised their hands. After fifteen minutes of continuing his lecture with his hand in the air, most in the room had noticed! Fifteen minutes! From that time on, my lectures consisted of no more than five minutes speaking to deliver concepts, followed by interaction with students in some verbal or physical manner – an approach called "dynamic teaching."

One teaching experience epitomizes this dynamic approach and reactions to it. Towards the end of one of my most enjoyable advanced design classes, I always assigned a complicated multi-step project. The class was divided into teams of five or six students and over a period of a few weeks, each team was required to develop design specifications, create their design, then present a quantitative solution.

During project development, there were many opportunities for each team to discuss their designs. They debated their approach, argued about assumptions, and offered best solutions. Although I moderated these discussions, I did not participate unless it was absolutely necessary. I told the students that I was acting as their direct supervisor and expected them to do most of the work. During one of these team dialogs, a verbal exchange was running loud, hot, and heavy. Debating the bases for each team's assumptions, some felt strongly about their assumptions and solutions. At the peak of the discussion, the department chairperson walked by the open classroom door. After the class, the chairperson asked me to attend at his office. With a worried look on his face, he asked: "What in the world was going on in your class?"

I answered: "Students were learning engineering, science, design, and team action by having one of their most effective learning experiences of their college career." After explaining to him what was going on, he reluctantly agreed that I may be right. I challenge any teacher to provide a more effective learning format.

As with most higher-education institutions, Cornell has alumni weekends. One thing returning students are asked is, "What professor was the most important and impressive during your time at Cornell?" Professors who are mentioned receive a note from the Dean indicating that a student had designated him or her the most important professor in their experience at Cornell. I received several of those notes over my career.

I felt that there was no course at Cornell that quantified the adverse effects on Earth caused by humans, so I started one: "Human Impact on Earth". I used a text developed at Harvard (*Living Dangerously*) where it was a required course for all their students. Human Impact on Earth was not required by any department at Cornell but it was promoted as one of the optional core courses for a new interdisciplinary degree in Environmental Science.

By the mid-1990s, it looked like web-based teaching/learning was going to be big in the educational world and Cornell devoted significant efforts using "eCornell" to encourage faculty to become involved in this new technology. Over the years, I developed comprehensive web experiences for three of my courses. Lecture notes, exams with solutions, study questions, design projects, homework assignments with solutions, links to additional information sources, and the like were all made available on the web. Initially, web-based activities did not change my approach in lecture, lab, or discussion-class meetings, although I expended twice the effort that it took to prepare just a lecture-based course. Eventually, I realized that almost none of the material I made available on the web was being used by the majority of students. As long as they received information, especially "information that might be included in exams", they spent little time on the course web site. While this mode of teaching must be a part of the future, the most effective form and shape remains to be determined.

I. A. 3. Early School and Work Experiences

Except for the opportunity to be with friends and to participate in extracurricular activities, my early school years meant little to me. It wasn't that I didn't enjoy school, but coursework was not very stimulating. My earliest recollections relate more to extracurricular activities than to learning. I enjoyed activities such as Key Club, leading roles in band and orchestra, and participation in student government as class vice president, etc. This led me to be more questioning and independent in my career, and not simply to follow prescribed directions.

My early background could be described as “poor” material-wise, but rich in environment and family. I was taught that if I wanted something, it would be up to me to figure out how to earn it. Work during summer vacations began early – I began working for my father in his gas filling station when I was 12 years old. One of my main sources of income, which enabled me to purchase most of my school clothes, was a large paper route. I don’t remember the number of people I served, but it was necessary for me to divide the papers into two stacks, taking half to a mid-point on the route, then coming back to the beginning, thus only carrying half of the total at any given time.

Perhaps my most important summer job was working at a shoe factory when I was in high school. The work was “piece work,” and at that time the factories were little more than “sweat shops”. The environment was dirty, hot, and very, very boring. Many of the younger men were juvenile delinquents with no interest beyond working to the weekends.

Although my father was a foreman in the factory, I didn’t work for him. I did work for one of his buddies, though, and in the same room as my older brother. I will never forget looking at him from across the room and seeing him shrouded in steam from a “boot lasting” machine, one of the hottest and toughest jobs in the plant. Since he was my idol, it made me feel terrible to see how hard he was working, and how harmful and difficult the conditions were.

After doing factory work for several summers, I knew that if I had to do this type of repetitive labor for the rest of my life, I would never survive. That incentive made me want to go to college to seek a better life.

When I reached my junior year in high school, I realized that one of the few directions to a more interesting and rich life was via education. Fortunately, that gave me the minimum amount of time to raise my average so that I might be acceptable to a college.

I had no idea how one paid for a higher education. I knew my brother had started college but had to drop out because of a lack of funds and, as a result, he was working full-time in the shoe factory. One day I had a conversation with my high school librarian that changed my life. In the middle of my senior year, she asked me what my plans were after I graduated, and I said that I would like to go to college, but I had no idea where I might find the money to do so. She told me that the daughter of the man who had built my high school (Lawrence High School, the same building and school from which my father had graduated) had supported a number of other Lawrence students, and she might consider supporting me.

I sent her a letter explaining that my father had recently gone through bankruptcy with his gas station and asked if she would loan me the money? She contacted me and invited me to visit her at her summer home in Maine, which I did in early Spring of my senior year. After a short discussion, Mrs. Alice Lawrence-Daub said that she would not loan me the college money, but she would *give* it to me, with three restrictions:

- I had to work all vacations and earn as much money as possible to support myself;
- I could not join a fraternity; and
- If in the future I could support young people in pursuing higher education, I would do that.

I was ecstatic and readily agreed to her conditions.

Over my four years at the University of Maine, I paid my room and board by working as a "residence counselor" (which required me to oversee the well-being of 20 to 40 underclassmen in dormitories), and Mrs. Alice Lawrence-Daub paid all my bills that I could not pay.

All of my graduate-school expenses, through post-doctoral studies, were paid by scholarships, many from the U.S. Environmental Protection Agency.

My first two undergraduate years focused on structural engineering with a minor in architectural engineering. This led to several semesters with more than 24 credit-hours and even Saturday morning drawing classes, scheduled from 8 a.m. to noon.

When I began to study Environmental Engineering, I found the layering of biology, chemistry, mathematics, physics, and engineering to be the area in which I could dedicate my life. Three degrees were received from the University of Maine, Manhattan College, and Stanford University. After receiving my Ph.D. at Stanford I spent a postdoctoral year split between the University of London's Westfield College and the British government Water Research Lab at Stevenage, England. Other courses were taken at NYU and UC-Berkeley.

I. B. TEACHING

I. B. 1. University Of Texas, Austin - 1969-1970

My first appointment as Assistant Professor was at the University of Texas (UT), Austin campus, with a student population of 45,000+. I was hired to replace a famous chair, Professor Wes Eckenfelder, who had moved from the University of Texas, Austin, to Vanderbilt University. Wes was one of my professors at Manhattan College and was part-owner of a consulting firm for which I worked during the summer of 1964, between completion of my Master's and the beginning of my Ph.D. degree. I was thankful to get the UT job as it was nearly impossible to be considered for a job while completing my post-doc in England.

I taught two graduate-level environmental design courses that year and found out that I knew lots about Environmental Engineering, but little about teaching. I had been deeply involved in research throughout my education and had not had any teaching assistantships. Fortunately, UT had a series of teaching seminars for new professors and they were of great help.

Living in the Southwest was a culture shock after my experience in England, and was very different from my New England background. Although I was given the opportunity to continue at UT, I felt it best to move closer to my roots in New England. After completion of the one-year appointment at UT, I decided to move back to more familiar territory and found an opportunity at the University of Vermont.

I. B. 2. University of Vermont - 1970-1973

The University of Vermont (UVM) was a challenging transition for me. I had assumed that the university experience would be similar, no matter the location. I chose a beautiful environment and assumed that good students and a research climate could be created. My starting salary was low at $12,000, but we were told that the Vermont scenery was part of our salary(!).

My teaching load for all three years at UVM made it very difficult for me to do research and maintain credible teaching. I headed up their new Environmental Engineering Graduate Program and I quickly learned the differences between world-class institutions like Stanford, factory-like systems like UT, and poorly supported systems like UVM. At the time, UVM was essentially a private school, since less than 25 percent of the school's budget was provided by the State.

My time there was characterized by financial constraints and academic/administrative wrestling. UVM's president, an M.D. who had been promoted from heading up the Medical School, told an engineering faculty meeting that due to financial exigency, UVM intended to eliminate the College of Engineering (COE) "because it was not needed for the State of Vermont".

The meaning of "academic freedom" also became clear early in my career, when I tried to organize faculty to argue against the COE elimination. I started to circulate a protest letter that outlined the many ways in which the COE supported the State. Unfortunately, my chairman threatened to fire me if I continued collecting signatures.

Perhaps the high-point of my stay at UVM was during the summer of 1972, when I organized an undergraduate team to compete for a large Student Originated Studies (SOS) National Science Foundation (NSF) project to redesign Burlington's waterfront. During my time in Burlington, the beautiful waterfront on Lake Champlain was devoid of almost any attractive beaches or tourist attractions. Instead, it was completely occupied by large oil storage tanks and a railroad switch-yard. Ten students from departments across the campus developed a new waterfront plan that included a hotel and conference center and several parks. Today, Burlington's waterfront development has incorporated many of our design elements, including a Hyatt Regency Conference center.

Although living in Vermont was enjoyable, I missed the high-quality Research and Development (R&D) culture I had experienced at Stanford as a graduate student. Besides regrets about leaving New England, I was hesitant to leave the Civil and Environmental Engineering discipline to join the Agricultural Engineering Department at Cornell. My primary reasons for making this discipline change related to my experiences in two rural states, Vermont and my native Maine. In the early 1970s, the magnitude of environmental challenges in rural areas was greater than those in the industrial/municipal field, which was the mainstay of Civil Engineering. This convinced me that the future action would be in the Agricultural Engineering discipline.

Some background into why I was willing to switch from a Civil Engineering Department at Vermont to an Agricultural Engineering Department at Cornell should be emphasized here. The huge magnitude of environmental challenges in rural America were emphasized when I came face to face with the number one rural environmental problem: impacts of septic tank use and management while teaching at the University of Vermont. I looked back on my college education and found no references at all to these anaerobic tank systems (followed by grass and soil zero-discharge systems, i.e., leach fields). None of the environmental engineering texts provided any background to this area. My environmental education basically ignored this area and assumed that this water-pollution-control technology was of little or no value.

When I began to look into this area, I discovered that nearly half of the U.S. population depended on this mysterious septic system to protect the environment, and that disposing of the solids pumped from these systems created a substantial problem. In fact, shortly after I began to work on the septage problem (the solids pumped from septic tanks), the United States Environmental Protection Agency (US EPA) designated this as the most serious sludge-management problem in the U.S. This background led me to organize my first national conference, which was developed around rural environmental engineering that focused on natural systems. It was also the use of these simple but important biological systems that sensitized me to the power of natural systems and to the poor state of understanding about what became known as "Ecological Engineering".

So with this background in rural environmental problems, when I had the chance to apply for a faculty position in the College of Agriculture and Life Sciences in the Agricultural Engineering Department, I did not hesitate to apply.

To support the growing number of graduate students in Environmental Engineering, when I decided to leave UVM for Cornell, I agreed to teach all of the courses I had developed. For my last year there, I had over 40 teaching contact hours per week, including two lab courses.

During that year, I also developed and ran a national conference on Rural Environmental Engineering, held in the spring of 1973 at the famous ski area in Stowe, Vermont. Over 300 people attended that meeting.

I. B. 3. Cornell University – 1973–2008

In the Spring of 1973, I jumped at the chance to interview for a position at Cornell University (CU), in Ithaca, New York. Upon visiting Ithaca for my job interview, I was pleasantly surprised to find an amazing institution surrounded by beautiful rural countryside. Eventually, I bragged to my Maine family and friends that Cornell is probably the most outstanding institution in the world where, only minutes from our library's doorstep, we are surrounded by beautiful farmland.

I have always felt that it was a great honor to work at Cornell University. Amazing, interesting, creative, and talented faculty and staff, as well as the greatest students in the world, surrounded me. My early years at Cornell were especially enjoyable because we were rich in resources that allowed faculty to have maximum flexibility. If a faculty member felt that an area was worth pursuing, administration would provide support. As long as a faculty member was successful, in terms of receiving support for his/her directions, administrative support followed.

My initial appointment at Cornell in 1973 required that I divide my responsibilities and time equally between teaching and research. After completing the marathon of teaching responsibilities at Vermont, imagine my surprise when the chairman of Agricultural Engineering told me that I could focus initially on building support for a research program, and that I would not have any teaching duties for my first year or so. That flexibility enabled me to grow my capabilities and my research program far more effectively than if I had immediately jumped into teaching. It also allowed me, in just a few years, to establish large grant support that focused on energy and agriculture.

The primary reason for my hiring by Cornell's Agricultural Engineering Department was to take on the teaching and research responsibilities of a very successful senior professor, Ray Loehr. Ray had been appointed the Associate Dean and Director of Research for the College of Agriculture and Life Sciences. Fortunately, Ray had already developed a US EPA traineeship program that supported a large number of graduate students, as well as several ground-breaking research directions. He had also been instrumental in organizing large annual Agricultural Waste Management conferences. My task was to take over these responsibilities as much as possible.

My interest in Rural Environmental Engineering was supported by an annual responsibility to prepare a review of agricultural waste management for one of the leading water-pollution-control journals. Doing this for five years provided an excellent in-depth knowledge of on-going activities in my field. This responsibility, along with my election to the Board of Directors of the Association of Environmental Engineering Professors, was early recognition of my leadership in this discipline.

When the extremely generous US EPA traineeship program downsized during this period, so was national enrollment in Environmental Engineering graduate programs. As a result, I volunteered to develop and conduct a national survey of the field. This enabled me to become familiar with all programs throughout the country.

These responsibilities led, in turn, to becoming a member of, and eventually head of, the research program committee for the Water Pollution Control Federation Conference. The program covered all aspects of water pollution with multiple sessions over the three-day conference. With over 5,000 attendees, it was the largest of its kind in the world at the time.

That experience led to interesting insights into leadership, research directions, and many aspects of water pollution research, and politics.

During my 40-year career in academia, I developed and taught several different courses: Introduction to Environmental Engineering, Design of Wastewater Treatment Systems, Design of Water Supply Systems, Agricultural Waste Management, Land Treatment of Wastes, Ecological Engineering, and Human Impact on Earth.

Although most of my teaching experiences were positive, one stands out in the opposite sense. There is a delicate relationship between doctoral students and their professors. My definition of success with Ph.D. students was that when they finished their course and research work, they were as good or better than me, especially in the area of their research dissertation. My greatest disappointment was with the only student who completed nearly all requirements for a Ph.D., but never completed his dissertation. Unfortunately, this student occurred early in my career and for a number of years was a full-time CU employee in my research team. We worked very closely together to address fundamental questions related to biofilm creation. At the time these topics were very poorly defined in the biofilm literature.

This student was mature and had several years of field experience as well as several years working with me in the lab. He was offered a position in the burgeoning field of bioremediation and decided to take it without completing his dissertation. This student never finished and an extensive study on biofilm formation was never published. This also was the end of my work on biofilms.

I. C. RESEARCH

I. C. 1. Beginning Biological Research

My research career began in 1962, during the summer of my junior year, when my advisor, Professor Otis Sproul, hired me to perform a number of jobs. The first was to develop a gas chromatograph test for organic acids in water, which was to be used to monitor anaerobic digesters. This was a great opportunity to learn about one of the more powerful wet-chemistry instruments, detector types, column construction, and packing materials, etc. It turned out to be a frustrating study, but one that taught me great patience, as well as numerous lab techniques.

My second research project was also with Prof. Sproul who, like all active and involved teachers at small State institutions, had heavy teaching and research activities, as well as doing outside consulting. My senior thesis project dealt with the organic material he had obtained from samples of Mississippi River water. The task was to develop a bioassay test that would indicate potential carcinogenic properties in organic extracts that smelled and looked like petrochemicals. Looking back on this research, it was clear that the project was very timely. Rachael Carson's *Silent Spring*, which became the lightning rod for carcinogens in the environment, was published in 1962, so Prof. Sproul was on the cutting edge and enabled me to see into an exciting, unknown, but challenging world.

The organic testing was conducted with a microbe (*Beggiatoa*) that was known to be highly susceptible to cell disruption. Visible cell disruption was considered an indicator of potential carcinogens. Early testing showed that many of the organics caused horrible mutants of the microbe to develop – changing the cell from a large, uniform rod-shape into large, living blobs with no structure.

Testing continued in an attempt to relate organic concentrations to cell disruption activities. Unfortunately, late in testing, controls were added to examine other materials that had been added to the organics prior to exposure to the microbes – alcohol, for example – which enabled the hydrophobic organics to be re-solubilized in water. These controls showed that some of the added materials, like alcohol, caused similar cell disruption to the extracted organics. This valuable, negative research lesson taught me the importance of carefully designed controls in wet research.

I. C. 2. Biological Research in Natural Systems

My first foray into more organized research occurred when I was a Master's student at Manhattan College in New York City. Although the degree program in which I was enrolled did not include a thesis (Master of Engineering), I wanted to work more closely with one of the several famous environmental engineers at the college. I volunteered to do a thesis under Prof. Donald J. O'Connor, a famous environmental modeler, and chose to develop a mathematical model of the influence microalgae had on a flowing stream.

That experience taught me a great deal. First, that my mathematical modeling capabilities were limited (and would probably remain so, as I found this area was not of particular interest to me). Second, but more importantly, was my limited understanding of natural systems, particularly the influences of microalgae on natural environmental aspects, such as dissolved oxygen and nutrient uptake and release. Although we began to understand the roll of nutrients in stimulating algal growth in nature in the early 1960s, much remained to be understood, and the term "ecosystem" was hardly known.

Upon enrolling in the Ph.D. program at Stanford University, my advisor, Professor Perry McCarty, a well-known authority in anaerobic digestion, asked me what topic I would like to pursue for my research dissertation. The only area with which I was familiar was algae. During my modeling work at the Master's level, I noticed that there seemed to be a hole in understanding what actually happens to microalgae after they grow. Some references suggested that they died and completely disappeared, while others indicated that some organic matter remained. It was obvious to me that some fraction of the algae must hang around for a long time; otherwise we would not be burning their remains as hydrocarbon fuels to support our modes of transportation.

In response to Professor McCarty's request for interests, I suggested the general field of algae and in particular, to define their role in the environment [Fig. 2]. He told me that I would have to find resources to support this direction of research, since none existed at the time. With his assistance, I wrote a research grant proposal to pursue the algal question and submitted it to what is now the US EPA. I was stunned when, a few months later, a three-year effort was fully funded. This support gave what few Ph.D. students ever have – a full-time research technician and lots of financial support. Because of this large support and Prof. McCarty's limited interest in the area, he essentially left me to run the study.

We hired a wonderful woman as the research technician, Dr. Victoria Mongird. While she was old enough to be my mother, or a younger grandmother, Victoria was exceptionally talented and we became good friends. She had been educated in Czechoslovakia and was part of a rich family. When World War II started, she had to leave her homeland and all of her worldly possessions were stolen, including her education documentation. That's why, with a Ph.D., she was hired as a technician.

One of the characteristics of this work was that some experiments shown in my thesis were over 600 days long. I should have known that my future biological research would be filled with long and complicated biological tests. Further details on the results of my Ph.D. work are discussed under *Section IV - Ecological Engineering.*

Figure 2. W. J. Jewell as a Ph.D. student at Stanford University with several algae experiments that lasted over 600 days.

Although I enjoyed teaching, my main stimulus came from riding on the frontiers of new and exciting research. During my career, I was able to attract over $13 million from outside funding sources. Although I was proud of this high level of support, it paled in comparison to support that was "just missed" by my efforts.

One of the earliest well-funded research grants became available in a competitive program from Standard Oil Company. In the late 1980s, I put together a university-wide proposal that made the short-list of three to establish a renewable energy R&D effort to be funded at $5 million per year for a period of five years. This was a huge amount of research support for the '80s. Although we did not win this effort, the preparation for it occupied my every waking moment for over a year.

Partly as a result of this failed effort, I became a more effective money chaser. After we found out that we did not win the Standard Oil competition, I pursued the background to understand why. In the process of this "discovery", I learned the number of competitors: Standard Oil received over 100 full proposals. Based on the amount of time and effort that over 20 faculty contributed to our proposal, I estimated the total cost of this competition to be as much as, or more than, the total amount of financial support to be awarded! From that point on, I chose to pick my fights more carefully and enter only when I had the advantage and had a good chance of success.

Another disappointment occurred when the New York State legislature proposed funding a $5 million research project to establish a renewable energy center. The research was to be located in my department and to be administered by me. I had nothing to do with establishing the bill and only heard on a Friday that the New York legislature was scheduled to vote on it the following Monday. Unfortunately, late into the night before the vote, wording of the bill was changed to support research into the incineration of municipal solid waste. The re-worded bill passed and the $5 million was awarded to Cornell's Department of Mechanical and Aerospace Engineering.

II. Anaerobic Digestion Fundamentals, Biofilms, and Innovative Process Creation

II. A. Anaerobic Digestion Fundamentals Driven by Oxygen Limiting Process

Although my dissertation was on a topic of ecological engineering dealing with aerobic processes, my Ph.D. advisor at Stanford was Professor Perry McCarty, one of the most famous anaerobic digestion researchers. So, early in my career, people doing fundamental anaerobic methane fermentation work surrounded me.

After a brief romance with pure oxygen-driven biological processes, most of my attention was devoted towards understanding anaerobic processes.

As soon as I had a lab at my disposal, I began working on harnessing anaerobic methane-producing processes. While at Stanford, I helped Jim Young run the first anaerobic biofilm processes to be developed – the anaerobic filter invented by Prof. McCarty. I became fascinated by a process that:

- encouraged bacteria to stick tightly to surfaces;
- created bubbles like an Alka Seltzer caused by methane formation; and
- resulted in purified clear water to exit the system with an energy by-product.

This was also the first time that I could actually see higher life forms in an anaerobic environment – anaerobic protozoa were plentiful and clearly visible in Jim Young's experimental anaerobic filters. Many questions were obvious to me, as in:

- How did the bugs know to stick to the surface? and,
- How was this microbial application different from suspended microbial processes, etc.?

II. B. Pure Oxygen Biological Processes and Limits

When pure oxygen became all the rage – primarily promoted by chemical companies marketing oxygen – I began to look at possibilities as well as limitations. Replacing air aeration with pure oxygen in conventional sewage treatment processes was the commercial direction being pursued. My first research was directed at finding a better biological system than those that existed, and that appeared to be a biofilm process. Using microbes in biofilms essentially eliminated much of the difficulty of separate processes required to remove suspended microbes from flowing water, and to recycle cells.

One of my first efforts was to document attachment, yields, and general kinetics of a biological treatment system that used pure oxygen. I made the argument that substituting pure oxygen for compressed air in biological treatment systems composed of suspended microbes was relatively worthless – like putting a Corvette engine in a Model T. Using pure oxygen in activated sludge did not take advantage of the added driving power of a gas that had the potential to provide five times the oxygen-liquid concentration. In addition, activated sludge with microbial concentrations of only 2 to 3 grams per liter was under one-tenth the known concentration of cells in aerobic biofilms. Clearly, a pure-oxygen-driven biofilm process was logical and would lead to a process with at least ten times the capability of conventionally suspended solids processes.

Early in this work I calculated the specific unit area (i.e., surface area of biofilm attachment per unit volume of reactor), and this led to the conclusion that solid media such as rocks and all other synthetic macro media, such as plastic materials, were extremely limited in their ability to generate a process with maximum biomass per unit of reactor volume. What conditions would lead to the reactor with the highest concentration of microbes, and thus a superior microbial application?

Around 1970, it was obvious to me that as microbial carrier particles became smaller, the surface area per unit volume increased dramatically, in fact, exponentially. It seemed like such a simple concept that others would have already made this observation, and if not, the wisdom of this observation would become obvious once I published such information. In retrospect, it appears that many interested in optimizing biological treatment still do not accept this concept.

But, wait! How does one keep extremely small particles in a flowing reactor? They would simply wash out if they were too small or too light.

At this time, chemical engineers had developed a process called a "fluidized bed" for a number of applications, many in physical processes such as incineration; however, fluidized beds used high velocities to enlarge the beds between 200% and 300% of the non-flowing settled bed. I reasoned that minimum expansion of the bed would be required to optimize biomass – say less than 20 percent expansion over a static bed. These lower-expansion velocities would enable smaller and lighter particles to be used as well. This became the basis for a new process, the *"Expanded Bed Biofilm Process"* [Fig. 3]. To this day, many in the field still refer to the process as a "fluidized bed", even though the process does not function well in a highly fluidized state, and one must sacrifice huge reactor volumes to support large bed volume expansions.

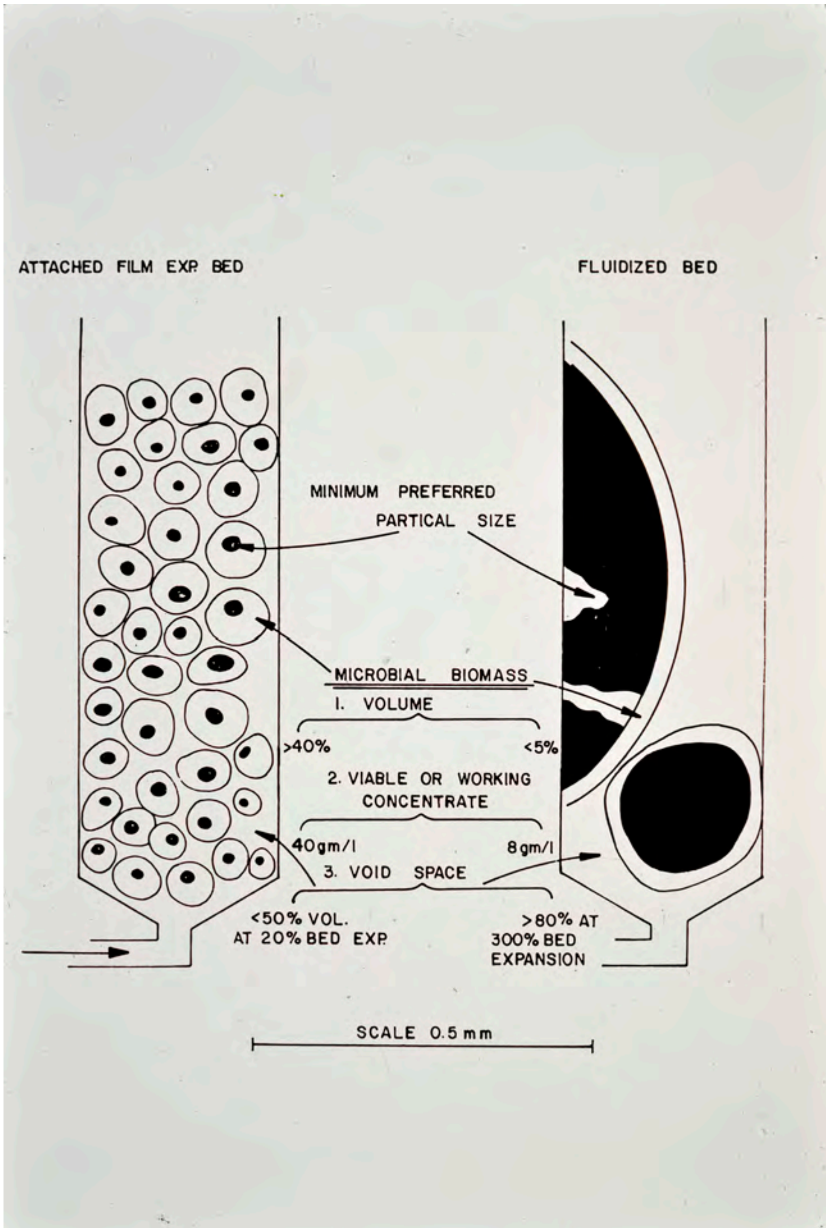


Figure 3. Illustration of difference between Jewell's biofilm process, anaerobic expanded bed, and fluidized beds emphasizing a ten-fold increase in capability of expanded beds over fluidized beds.

An important first step was to define the fundamentals of oxygen transfer into biofilms, and this study was conducted with a plastic media and direct oxygen injection. Submerged optimized plastic media was used in extensive and large pilot filters. Over a relatively short period, thick biofilms began to clog the plastic media, even though the void space was considerably larger at over 95 percent of the reactor volume. This was an exclamation point that high yields in aerobic processes would require careful maintenance and that excess microbes would be a problem [Fig. 4].

Figure 4. Early experiments with commercially available static biofilm support and pure oxygen emphasized limits of aerobic processes and problems of high aerobic yields and media clogging. This resulted in early abandonment of most aerobic biofilm applications.

Aerobic film management and surface area relationships led me to develop the first version of an expanded bed using pure oxygen. Expansion control was obtained using external oxygen addition via recirculation. This resulted in a very efficient system with an abundance of process potential.

This process improvement became my first focus of an attempt to commercialize a new concept. Some of the biggest players in pure oxygen became interested in the process, and this interest, and subsequent secrecy and consulting agreements, became an important part of my early education in innovative technology development and commercialization.

Eventually a non-disclosure agreement was made with one of the largest waste treatment equipment companies – FMC Corporation. They committed large amounts of capital to piloting the pure oxygen expanded bed at their largest research facility in California; however, they did not communicate with me during this time. After spending over a year, and more than a quarter of a million dollars, I was contacted and asked leading questions, which indicated to me that they were having second thoughts. They asked me to fly to California to meet with them and review their results – essentially after the fact.

Upon entering the lab where a number of impressive clear plastic pilot expanded beds were operating, I took one look and said, "I see that these units are failing."

The research engineer looked at me and said, "How do you know that?"

I replied, "You can tell that they are oxygen-limited by the color of the biofilm." All reactors were either grey or black, indicating that the biofilms were not aerobic. Aerobic biofilms with sufficient oxygen have a distinctive pink color.

Shortly after that, I met with a VP of the company and several of their research engineers. I was shown data that they developed that demonstrated poor system performance. Even though I indicated to them that this was not unexpected given the operating conditions, they concluded that they had expended their budget and would no longer be interested in further development of the concept.

At that point in the discussion, I indicated that another approach might be more beneficial, and that was to abandon oxygen entirely and go with anaerobic conditions. Instead of acknowledging that this was a great insight, it was pretty clear they felt that completely reversing directions of the research was too drastic to consider, effectively ending my association with them.

That experience led to an important, albeit disturbing, situation that affected activities throughout my career. If one of the leading R&D groups, with significant resources, cannot develop innovative concepts, or have difficulty recognizing obviously improved directions, perhaps personal venturing into the commercial arena may be necessary for successful technology development and transfer.

In addition, that combination of events led me to a qualitative examination of the relationship of microbial substrate loading, their yields, and the retention times for microbes. The result emphasized that aerobic systems could not be used in heavily loaded systems, because the high yields and rapid growth would make the microbial retention times short and therefore less efficient. Conversely, the lower anaerobic yields (one-third or less that of aerobic systems) theoretically enabled highly loaded systems to out-perform aerobic systems.

II. C. Introducing the Anaerobic Expanded-Bed Process – Revolutionizing Sewage Treatment

By the early 1970s, it became clear that waste management energy consumption would become a significant concern in all activities. For this reason, I realized that further work on energy-consuming pollution control processes was all but dead, and that energy-producing concepts would hold the greatest potential. That, in fact, was the beginning of my dedication to more efficient engineering using natural processes, or *"Ecological Engineering"*.

Early experiments with fused diatomaceous earth particles between 100 and 200 microns in diameter led to impressive organic conversions [Fig. 5]. Applying conventional kinetic models did not seem to fit this system [Fig. 6]. It appeared that extremely large surface areas resulted in performances never observed before.

Figure 5. Fused diatomaceous earth particles without biofilm used in development of the anaerobic expanded bed biofilm concept.

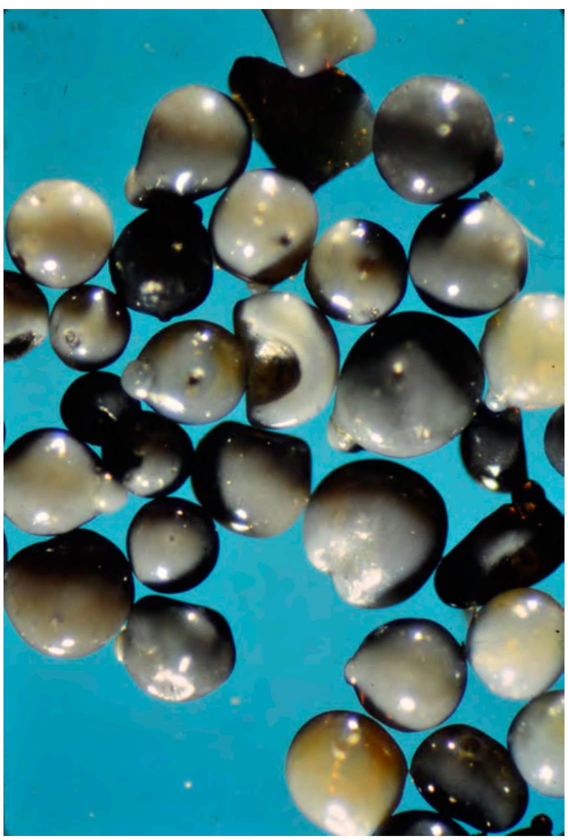


Figure 6. AFEB particles with mature biofilm. Particles had diameters between 100 and 200 micrometers and these films had a depth of about 20 microns.

Looking back at this time, and while interacting with my first Ph.D. candidate, I realized that I was willing to walk way out on thin ice and take my student with me. A condition of much of my research, and guidance of my graduate students, was that it was a waste of time doing a research project that enabled one to confirm a second or third significant figure on something someone else had already done.

Exciting research is when one enters "*no-persons land* " in a critical area where, if successful, the results would have a significant and positive impact on some environmental problem.

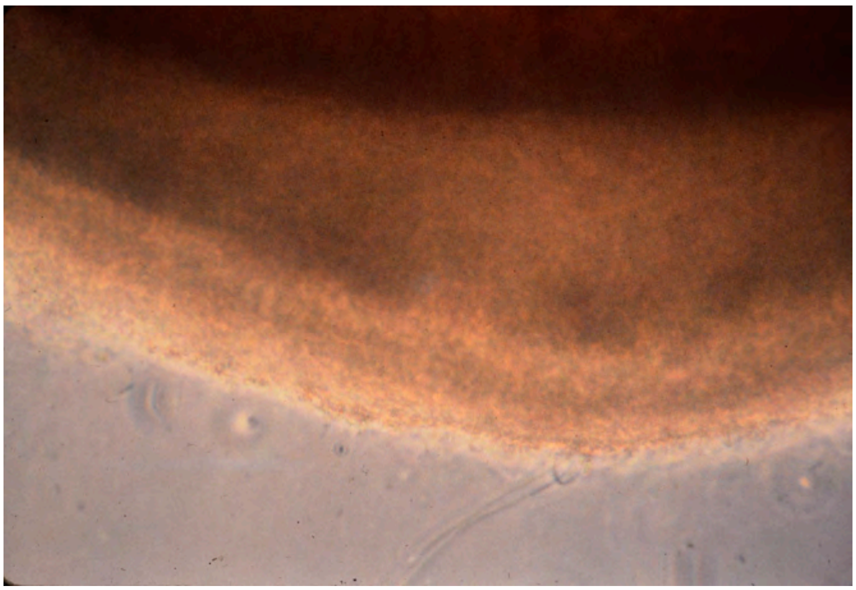


Figure 7. Micrograph of anaerobic biofilm.

My first Ph.D. student, Michael Switzenbaum (former head of Civil Engineering Department, Marquette University, now retired), was a joyous student willing to follow his professor down any road, no matter the danger. For Mike's Ph.D. dissertation, I outlined the following:

A small-particle anaerobic reactor appears to be capable of doing things that were not possible with any other microbial processes. "What if ", I challenged, "we could show that an anaerobic process could function at low temperatures and low substrate concentrations?"

Of course, this was heresy! Anaerobes do not function under cold conditions or with dilute substrates!

But what if they could be made to do so? A successful or proven result could lead to sewage treatment facilities producing energy rather than consuming the billions of dollars' worth of electricity used to run the 10,000+ conventional aerobic waste treatment facilities!

So, off Mike went into the horizon running anaerobic expanded beds on simulated sewage at temperatures down to 0 C. And guess what? They worked well! At low temperatures and very dilute substrate concentrations, organic removal results with my biofilm processes were as efficient as conventional aerobic processes even at equivalent hydraulic retention times. To put the crowning exclamation point on the outcomes, Mike ran Ithaca's sewage through his lab units at the end of the definitive testing and showed that the process worked as well with real world material. Unheard-of results! And heresy to most biological waste treatment engineers.

At the time that Mike finished his work in 1978, the Association of Environmental Engineers and Scientists (AEEP at the time) was giving an annual award to the best Ph.D. dissertation. Since Mike's thesis took on two of the most rigidly held and accepted beliefs about a common process, and showed that a whole new world could exist, I figured that his would be the "slam dunk" best thesis. I had no doubt that my colleagues would see the outstanding work that Mike had accomplished, including its very important applications.

Alas, my idealism was shattered when Mike did not receive the recognition I had expected him to receive.

Fundamental research on the anaerobic expanded bed continued for the next several decades but without, in my humble opinion, the kind of recognition that it deserved. (*See comments under Commercial Activities*.) Today, the most popular engineering design texts credit Mike and me as the founders of anaerobic sewage treatment … only four decades later.

Over the next two decades, we built on the fundamental understanding of anaerobic films and their potential applications. As a result of Mike's work, we showed that anaerobic biofilms had exceptional characteristics that made them efficient under a number of challenging situations. First, these biofilms were much thinner and denser [Fig. 7] than had been previously observed. Relatively low organic loadings [Fig. 8] resulted in biofilm densities that actually approached that of wood – 40 percent of wet biofilm was dry matter. This led to the hypothesis that processes in the future could have biomass concentrations approaching 400 grams per liter of reactor – if we could devise a way to enable the substrates to interact with films without creating too much void space. Even given the sacrifice of the films to inert attachment particles and void space, it should be possible to achieve microbial masses of up to 200 grams per liter of reactor. This is about 100 times the microbial mass found in many conventional biological processes [Fig. 9].

So what if the anaerobes work very slowly? Even if they worked at one percent of aerobic competitors, they would still work twice as fast per unit reactor volume as aerobic alternatives. This meant that anaerobic reactors could be the same size or smaller than conventional systems, but they would produce energy rather than consume it!

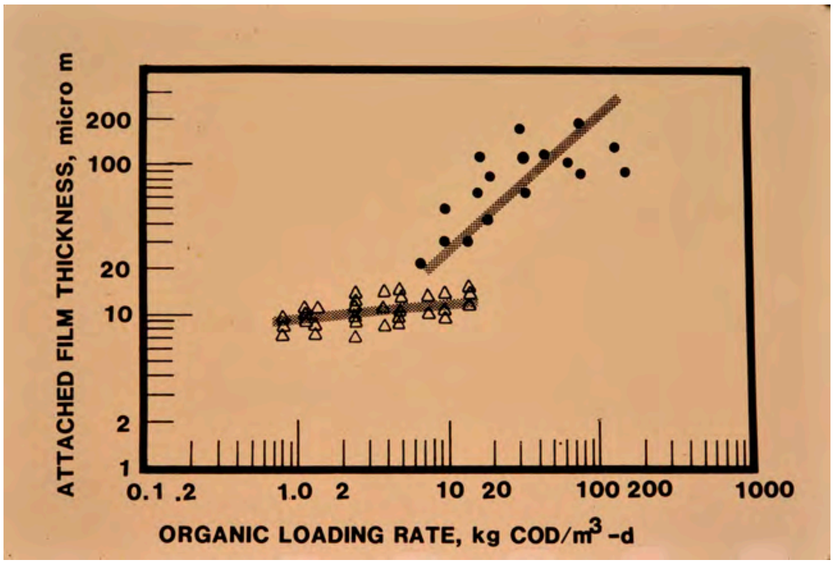


Figure 8. One of the two most surprising developments in anaerobic biofilm reactors: showing the relationship between bioreactor volumetric loading rate and steady state biofilm depths.

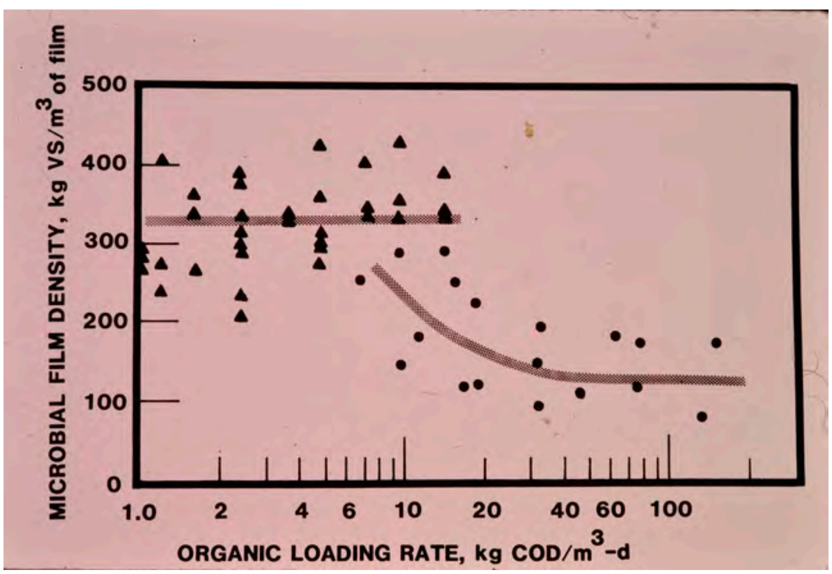


Figure 9. One of the two most surprising developments in anaerobic biofilm reactors: showing the relationship between bioreactor volumetric loading rate and steady-state biofilm density. The high biofilm density sets the upper limit on bioreactor biomass attainable in biofilm reactors.

I was asked to give keynote speeches at two world conferences, in 1982 and 1984, that focused on biofilm processes and their pollution control potentials. (*See comments under Commercial Activities for further discussion of this process.*) In addition, in 1985 I was asked to write a review[3] article on anaerobic sewage treatment for the leading environmental journal.

3. W. J. Jewell, "Anaerobic Sewage Treatment," in *Environmental Science and Technology* 21.1 (1987): 14-21.

By that time, it was clear that anaerobic treatment was recognized worldwide as an important concept, but was not so in the U.S. A Dutch colleague, G. Lettinga, had successfully developed an anaerobic process that was similar to my expanded bed, but it was introduced as a bioreactor without attachment media. Because of important energy implications and the unique nature of anaerobic wastewater treatment, the Dutch government sponsored full-scale applications of Professor Lettinga's process throughout the world. Along with a well-funded R&D group in the Netherlands, Prof. Lettinga has been responsible for moving anaerobic treatment into widespread applications, except with few or no applications, especially to sewage, in the U.S.

Subsequent work focused on applying biofilm reactors to thermophilic uses, defining suspended solids conversions, and sulfur interactions. It became clear over time that the side reactions with sulfur and nitrogen would drive the usefulness of many of these high-rate processes. Professors G. Schraa and Mike McFarland pursued high-temperature applications, and particle and sulfur interactions, respectively. Both of their work stand alone in defining potential applications under unusual microbial conditions.

Because of a limited amount of R&D support, further fundamental work on anaerobic biofilms was discontinued in the early 1990s.

II. D. Innovative Process Introduction

II. D. 1. Dry Anaerobic Composting or High-Solids Digestion

Many anaerobic applications, especially in the renewable energy world, must deal with materials that are relatively dry, such as crop residues, animal waste with significant amounts of bedding, municipal solid waste, and the like. Conventional wisdom holds that anaerobic processes only operate in high moisture conditions. Sludge digesters, for example, usually operate at solid concentrations of 10 to 30 grams of dry matter per liter or kilogram of wet reactor volume, i.e., one to three percent dry matter.

In the early 1980s, I wanted to define how "available water" affected methane production. Walter Wujcik, my Ph.D. student, decided to work on that topic for his dissertation. This was the first work to define the upper limits of dry matter concentrations in anaerobic digestion. His work showed very clearly that methanogens were not kinetically limited up to dry matter concentrations of 250 grams per kilogram of reactor, i.e., 25 percent dry matter; however, at 250 to 300 dry grams per liter of reactor, kinetics declined drastically. That work paved the way towards “anaerobic composting”. Today, several European and North American companies market processes based on this work.

A Belgian company has reported methane production rates as high as 10 volumes of methane per volume of reactor when processing organic fractions of municipal solid waste (MSW). I postulated that maximum rates for efficient dry fermentations would eventually approach this value. This is 100 times the methane production rates observed in conventional sewage sludge digesters.

II. D. 2. Liquid (Aerobic) Composting

Over the years, a number of innovative directions were identified using fundamentals of biological processes. These included biofilm applications, as well as new approaches to the processing of solids.

Conventional aerobic composting takes advantage of the reaction’s biological heat to autoheat wastes up to pasteurization temperatures. This has a number of advantages, but disadvantages as well. Among the disadvantages is that many composting applications are applied to wet wastes, such as sewage sludge that is generated with high moisture content. Before composting can be applied, wet solids must be squeezed and dried with considerable investment in technology and energy to reach autoheating conditions.

Another drawback is that some microbes involved in conventional composting are dangerous and harmful – such as certain fungi and fungi spores. Composting facilities must be located where the aerosolized drift will not be a potential respiratory problem.

Liquid aerobic composting eliminates the need for all prior treatment and it does not involve fungi. The key to this process was the invention of high-shear field aerators that transferred oxygen at efficiencies unheard of prior to their application. In order to transfer enough oxygen, the aerators strip heat via the evaporation of water. This prevents autoheating of liquid slurries such as sewage sludge. New high-shear field aerators conserve energy so that even in dilute liquid systems, the energy released during aerobic organic decomposition is sufficient to autoheat reactors to pasteurization temperatures.

Our unique contribution to this area was to document the capabilities at full scale and to identify theory and rationale that allowed this unique application to be successful. Based on our work, several companies now market this system of high-temperature treatment of organics requiring limited energy input – and zero heating energy – to achieve high-rate thermophilic reactions and pathogen destruction.

II. D. 3. Biodryer

While working with the theory of exothermic heat of biological reactions, I became interested in moisture removal processes. Quantifying heat generated by biological reactions (exothermic heat generated by the aerobic heating of organic oxidation) showed that in many instances, excess heat was available beyond that necessary to raise the temperature of the material to thermophilic zones. In fact, enough excess energy was available to evaporate large quantities of water. Based on this theoretical analysis, we designed, tested, and confirmed that well-insulated reactors could achieve thermophilic conditions while achieving a dried effluent. This led to a "biodryer" process that is part of the language of waste management today.

II. D. 4. Closed Systems Aquaculture Via High-Rate Biofilm Processes

When complete-recycle aquaculture systems began to be developed, it was clear that pollution control would be a key to enabling this approach to move forward. My biofilm work suggested many possible applications, and aquaculture systems appeared to be an excellent area in which to test their potential. Ammonia generation and removal is one of the greatest challenges to recycling aquaculture. Examination of the theory and potential of biofilms to convert ammonia-nitrogen showed that an incredibly short retention period of 60 seconds should be adequate to completely remove ammonia-nitrogen (i.e., convert it to non-toxic oxidized forms). A full-scale system was constructed and confirmed that this was possible.

Of course, complete removal of nitrogen would be more beneficial and this would reduce the required pH chemical manipulations. Further development showed that a biofilm system could be operated in such a way as to eliminate nitrogen after ammonification, followed by nitrification and denitrification with the generation of nitrogen gas.

Successful treatment in this area led to efforts to enter the commercial world with the technology. Although I was successful in designing and raising funds to implement this technology, ethical questions arose with persons with whom we had chosen to partner. Because of these problems, commercialization in this area was terminated. *See a full description of this adventure under the "Commercial" section.*

III. Energy and Agriculture

In 1973, several situations combined to launch my career at Cornell in a big way. The U.S. was entering its first real energy crisis and I had already focused on renewable energy, rural communities, and anaerobic digestion. Gasoline was being rationed and there was discussion of energy security for farms. It was logical for me to begin looking at the interaction between agriculture and energy, so that became a focus for me, with the possibility of energy-from-waste processing always a background topic. My first million-dollar grant came easily from the U.S. Energy Research and Development Agency (predecessor of the U.S. Department of Energy). This feasibility study included a half-dozen other professors, more senior than me, and the same number of different departments ranging from engineering to social welfare and economics.

III. A. Energy-Independent Food Production Via Anaerobic Digestion

In the early 1970s, relatively little was known about the exact amount of fuel it took to produce food on farms. One of the most important outcomes of this effort, and perhaps of my whole career, was to show that enough energy could be produced by processing wastes via anaerobic digestion to supply all on-farm energy requirements, including transportation fuel. Our multi-disciplinary study focused on small dairies and medium-sized beef feedlots (1,000 head). Our estimates showed that methane could replace all heat and electricity, and if converted to transportation fuel, could provide that portion of energy as well. Energy-independent food production could be achieved if all farms incorporated anaerobic digestion of wastes. But cost was another matter.

Universal application of anaerobic digestion made good scientific sense because pollution control was becoming (and continues to be) a major challenge for farms. It seemed to make good sense to use anaerobic systems where bacteria could cleave off just the carbon, then convert it into a clean, valuable, substitute natural gas, while deodorizing wastes and leaving all soil humus and nutrients to be recycled.

After our large feasibility study produced such positive results, we received another million dollars or so and a charge from the U.S. Department of Energy (US DOE) to "develop a cost-effective digester for small farms". Our same team continued its work, but the focus was more on digestion fundamentals, initially at lab scale. In order to provide a proper base for this effort, we gathered all researchers in the field and held a major conference on energy and agriculture – the first major national conference to focus on renewable fuel on farms. Those conference proceedings (1975) still provide interesting insight into activity in this nascent field.

Our team was flying along making major advances in biofilm applications, dry fermentation, and agricultural-energy systems analysis, when a strange and personally disturbing event occurred. Federal bureaucracy was still transitioning and project management was undergoing constant change. A former dean of engineering, much senior to me, replaced our government project manager. One day he called and said that he suspected me of mis-using our research funds. For a young investigator who always followed the rules, this came as an enormous surprise. He went on to tell me that after the national symposium where I was to present our progress, scheduled for the University of Illinois, I would be called to "testify" at a hearing of my peers to explain my management! I had no idea what that meant, and had never heard of anything like it before, or since.

My public presentation at the symposium was greeted with a near-standing ovation as we had accomplished a great deal in very little time. Unfortunately, my Cornell project manager had other ideas, and after the meeting, I appeared before the peer group and tried to answer their many questions. The group included a chaired professor, consultant and professor, and the US DOE project manager. This group examined my project as if I had been accused of cheating the government. After an hour of trying to defend the manner and direction of our large Cornell project, I stopped answering their questions. I said that if they wanted me to do something else with my grant, all they had to do was tell me. I guess that is what the project manager wanted. He said that I had to drop all "multi-disciplinary" aspects of the project, get rid of all co-investigators (of which there were seven) and do one thing – develop a small-scale, low-cost digester for dairies.

This was a very disappointing development for me. Even though my principal focus was to be supported, I felt that the multi-disciplinary approach was yielding great insight. Rural sociology might not be what catalyzed progress, but it would have assisted in understanding how renewable energy policy could impact agriculture.

As I returned home from this challenging meeting, I ran into the well-known consultant at the Chicago airport. He correctly noted that I was pretty depressed at the outcome of the weird Illinois meeting and said something that I will never forget. After saying that he knew that I was not too pleased with the outcome of the meeting, he said:

"Bill, you know that you are doing some pretty impressive things. But, if you do one thing well, clearly ahead of your peers, that's great! If you do two things, that's good as well. But if you are doing more … that just makes your peers, well, it makes us look bad, and they (we) are not especially happy."

So, our huge Cornell effort became one-dimensional and we will never know how things would have progressed if the team had remained together. From that point on, when research projects required a "multi-disciplinary team", I viewed them with skepticism.

III. B. Cost-Effective Dairy Digestion System

At the end of our first Agricultural-Energy conference, I moderated a discussion with over 150 people where we discussed needs for future energy production on farms. At one point in the discussion, I said that although multiple digesters were built on farms in Europe beginning immediately after World War II, as of 1975, none existed in the U.S. A voice from the back said that that was not true, that he had built a digester at his beef operation in Ludington, Michigan. After the conference, I met with the farmer and made arrangements to visit his farm. In retrospect, this visit resulted in modifying my thoughts and humility in relation to the real world [Fig. 10].

Figure 10. Picture of the first plug-flow digester developed and installed at a beef feedlot at Ludington, Michigan, in the early 1970s, inspiration for Prof. Jewell to attack digester design from an entirely different direction from all others.

The Ludington digester was designed by three people with little knowledge of the fundamentals of digestion, but with their design firmly based on the need to be cost-effective. The trio consisted of a farmer, a chemical engineer, and a carpenter/contractor. The digester was constructed with soil supporting the sides, the digester tank itself was completely made of a rubber-like liner material, and it was a plug-flow reactor.

Everything they had done broke all the engineering principles of anaerobic digester operation and design. Influent solids concentrations were too high; it needed to be mixed and they had no mixing at all (by definition of plug-flow); construction materials were unknown in this application; and plug-flow, again by definition, would result in a system failure. Basically, the practical Michigan approach stripped away almost all costly components and operated a digester different from anything that had been done previously.

Upon returning to my lab and research team, I decided that our approach would follow similar directions [Fig. 11]. We would start with the simplest system and show through good engineering research why various aspects of the plug-flow system will **NOT BE** acceptable. Then we would introduce minimum mixing, for example, to show how much they would need to be modified to meet strict engineering requirements, while lowering costs of absurdly small digesters for small farms.

Figure 11. Lab-scale plug-flow bioreactor analysis is theoretically composed of a large number of completely mixed reactors in series.

Although, theoretically, a generic plug-flow design is known to be the most efficient bioreactor, it had always been assumed that complex anaerobic methane fermentation would fail in this application. But in fact, classic chemical and environmental engineering texts clearly showed that a plug-flow

Figure 12. Three-cow plug-flow digester model studied for three years to document limitations of unmixed dairy cow manure digestion bioreactor. Construction of this pilot lab unit used low cost flexible liner material that was eventually used in full-scale systems.

reactor at least one-fifth the size of the commonly accepted design (a completely mixed bioreactor) would achieve the same efficiency of organic conversion. This theory provided great incentive to consider plug-flow reactors, even if we expected that they would fail. We ran lab-scale plug-flow digesters for a year, then built a three-cow pilot digester [Fig. 12] using a completely instrumented plug-flow design, and incorporated experiments with low-cost construction materials, such as a flexible liner.

After several years and another million dollars or so of wet research, we concluded that animal waste digesters, mainly dairy waste digesters, could be highly successful with the simplest of systems. These systems incorporated unmixed digesters, with no dilution; used a higher input of solids than had ever been used before (12 to 15 percent dry matter, unlike the tens of thousands of sludge digesters that were operating with one-tenth this input of solids); and operational digester solids of 60 to 80 grams dry matter per liter of reactor.

Because dairy waste is well inoculated with methanogenic microbes, plug-flow (i.e., no mixing required) was the obvious reactor type of choice, and failure could be easily avoided with appropriate loading controls.

That led to our proposal to build and demonstrate, at full scale, a one-family dairy digester system sized for 50 lactating cows. To prove the effectiveness of our design, we recommended running this in parallel with a conventional, full-scale, completely mixed digester, constructed of concrete and steel [Figs. 13, 14, 15, and 16].

Figure 13. Cornell's full-scale 50-cow dairy manure control completely mixed digester operated in parallel with the innovative plug-flow design for seven years. Of particular value of this long-term project included the longest comparison of full-scale digester options operated in extremely cold climates.

This full-scale system comparison operated for over seven years. That was the largest and most comprehensive full-scale design comparison ever made between an innovative plug-flow design and the common, completely mixed design. Throughout the comparison period, the plug-flow design operated more efficiently and with fewer problems than the more expensive, completely mixed design.

Figure 14. Winter view of Jewell's plug-flow digester sized for a small dairy.

Figure 15. Initial installation of flexible liner in Jewell's plug-flow digester sized for a 50-cow dairy. The biogas recovery liner is being lifted by biogas generation prior to insulation and weather cover addition.

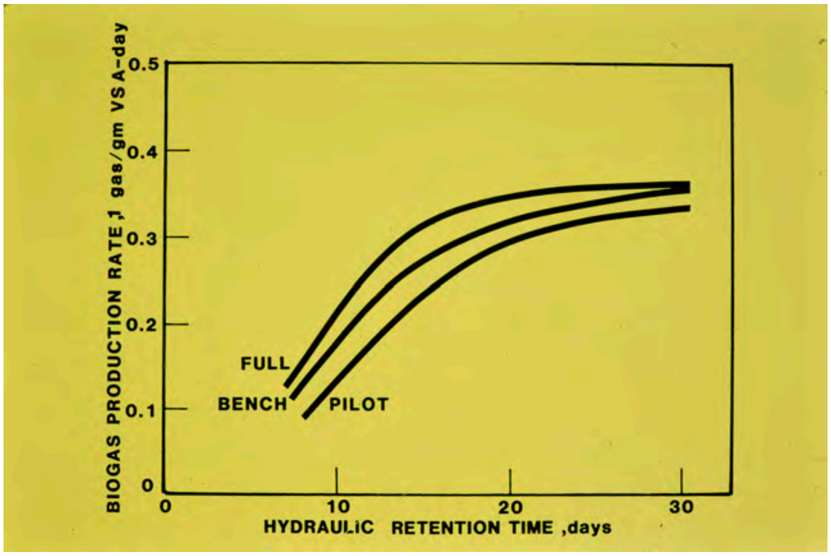


Figure 16. Comparison of data from lab-bench-scale to pilot-scale to full-scale 100-cow dairy manure anaerobic digestion over a seven-year test program.

Another aspect of the full-scale comparison was the documentation of the reliability of small digester systems. Over the seven-year period, the "down-time" for our one innovative system was exceptionally small, emphasizing the robustness of the system. When we scaled up the system, the reliability of the system was further proven.

Early in the operation of the full-scale system, it was clear that farmers were skeptical of the thin rubber-like material that formed the reactor. The digester was located only a few feet from a wooden structure that housed instruments and digester controls and a combined heat and power internal-combustion engine. First questions from visitors usually related to the safety of such a design and the danger of explosion or fire. In order to address those safety and fire concerns, we decided to create the worst-case accident by throwing a burning gasoline-soaked rag on top of the rubber liner (energy content of the methane gas contained under the rubber-like liner was calculated to equal three sticks of dynamite).

We expected the digester liner material to quickly burn through, ignite the biogas, and collapse the cover onto the wet digesting manure, and that would be the end of the accident [Fig. 17]. A movie documenting this safety test was produced for insurance companies. Flames reached 40-feet high but the 3,000 cubic feet of biogas stored over the digesting manure was quickly consumed and the flames died out. We knew that an explosion would not occur unless there was a critical methane/oxygen mixture, and this will not happen with an operating digester.

Figure 17. Burning plug-flow digester with flexible rubber-like liner showing result of "worst case" accident when a burning rag is thrown on top of the reactor.

Figure 18. Fire damage to Cornell University's plug-flow digester after intentional "accident" fire was extinguished. The top was replaced and within 24 hours biogas production was back to normal.

Perhaps most important with any low-cost design is the degree to which severe interruptions will disrupt the operation. Within 24 hours of the fire, a new top was installed and the digester energy production was back to normal [Fig. 18].

Contrast that to what happens when a rigid-tank digester experiences reactor implosions or damage to the structure. In a number of experimental and commercial units where damage has occurred, repairing and placing the system back in operation took months to years, and often resulted in abandoning the system due to high replacement costs.

In 1982, with assistance from combustion engineers, including Dr. Rick Koelsch, we added a small combined heat and power unit (previously called "co-generation") to consume the biogas. This was an off-the-shelf spark-ignited Cummings engine and a 10 kW electric generator with heat recovery.

Figure 19. Several years of research were devoted to growing, harvesting, and estimating transport and storage problems for crops such as hybrid poplar and high-yield sorghum shown in this photo. New York sorghum is on the left, high-yield Texas sorghum is on the right with Prof. Jewell.

Figure 20. Commercial digester in Ontario, Canada, built at a beef feedlot. This digester is the same bioreactor design used in thousands of sewage sludge digesters, i.e., a completely mixed design; specifically, it's the design that Jewell feels is not acceptable on small farms. This beef feedlot with several thousand head went bankrupt shortly after implementation of this multi-million dollar digester system.

This multi-year effort generated much large-scale information:

- electricity generation contained over 25% of the input energy in the biogas;
- energy recovered in hot water from the engine represented over 50% of the gross input of energy; and
- a quarter of the input energy was lost as heat.

Our primary conclusion at the time was that the technology was available, but that it was not robust at a small scale. Thousands of full-scale co-generation systems operated on biogas in sewage treatment plants, but they were ten to one hundred times larger than our test unit. Today, lack of availability of small-scale units still limits the viability of the technology for smaller farms.

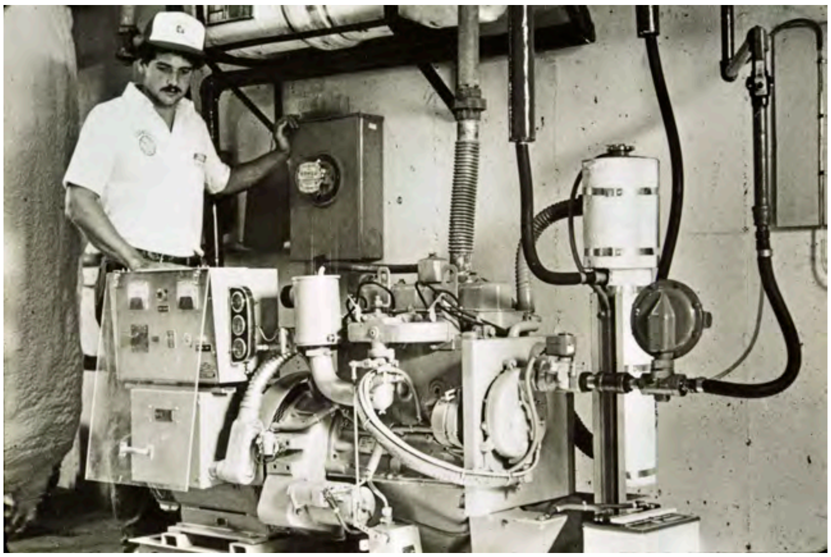


Figure 21. Combined power and heat recovery engine tested for several years at Jewell's small dairy digester development project.

For over a decade, our work continued to document the role of renewable energy in animal agriculture and small farms [Figs. 19 and 20].

Today, there are significant numbers of practicing engineers with limited reactor design experience who still believe that plug-flow digesters constructed of low-cost materials represent bad design. In fact, fundamental reactor design, with first-order reaction kinetics, show that a plug-flow digester can achieve equivalent conversion to a completely mixed conventional design in only 5 percent of the reactor volume; i.e., the Jewell-Cornell design is 20 times more efficient than a conventional design. This basic information is found in "introduction to reactor analysis" chapters in textbooks over 50 years old.

Of course, there are restrictions to our low-cost approach. If the unit has no power input for mixing, the viscosity of the reactor must be such that solids do not separate, and digesting mass must be able to flow through the system using gravity forces. This means that special attention must be paid to floating or settling material. Even if the reactor is susceptible to other variations, our work strongly suggests that low-cost soil-supported structures constructed with flexible liner materials can drastically lower capital investment.

Partly to address critiques that the Cornell design could not be practical, the largest system in the world was constructed by my private company in 1982. *See comments under Commercial Activity section.*

As the energy crisis of the '70s became a distant memory, work on waste management began to receive less attention. Interest shifted for about a decade to the possibilities of providing significantly more energy from energy crops or crop residues. In a *Cornell Engineering Quarterly* issue,[4] I reviewed for the first time the possibilities and impact of regional renewable bioenergy systems by focusing on the potential energy and the economic impact of such systems. One of the main messages from that article emphasized the flow of money and potential impact on rural communities.

Today (as well as when the article was first written), a 10,000-person community sends millions of dollars of its hard-earned money out of rural areas. If crops were grown for energy, farmers who would transport biomass a reasonable distance could supply a large fraction of a community's energy needs. Millions of dollars would circulate in the community, creating other opportunities and employment. It is likely that additional jobs created by rural biorefineries could eliminate unemployment. Agriculture would be energized and expanded. I have often repeated to anyone who would listen, from researchers to investors, that if we wanted to demonstrate the most important thing in relation to agriculture and energy, we would show that a small rural community of 10,000+ people could be completely food-sustainable and energy-independent.

My profile in this area reached its peak when I was designated as "The University Professor" for a small Texas college and invited to give a talk on the topic of energy and agriculture. Over 5,000 people attended this lecture, and it made me feel like a rock star – at least for a short period.

III. C. National Award for Innovative Energy R&D

In 1988, our work was honored when Ron Isaacson, my project manager for a number of years, and I received both a New York Governor's award and a US DOE National award for outstanding

4. William J. Jewell, "Natural Gas from Agricultural Wastes," *Engineering: Cornell Quarterly*, 12.1 (Spring 1977): 14-24.

contributions to our Nation's energy status. The DOE presentation was a fancy Washington, D.C., affair where the "President's Own Marine Band" played for us and the Secretary of US DOE attached pins to our lapels.

III. D. Regional Dairy Digester Systems

There are over 6,000 dairies in the State of New York and many are faced with increasing economic and pollution-control problems. Several areas have thousands of dairy animals within a few miles of each other. For this reason, a number of locations are considering trucking animal wastes to centralized processing sites. We worked with the Soil Conservation Service to examine the feasibility of such operations. Our conclusion, for at least one area of New York that was densely populated by dairies, was that it could be an economically feasible operation. However, careful consideration had to be given to transportation costs and complexities.

III. E. Future Systems – Resource-Recovery Animal Waste Systems – Introducing Pollution-Free, Energy-Independent Farm Concepts

Throughout our work on digesters at dairies, I maintained that two general policies must be undertaken before digesters would be widely implemented. First, the technology was, and is, too complex to provide custom designs for every farmer, then to build those custom units, then turn all operating responsibilities over to the farmer. Our farmers already work too hard producing and preparing safe and secure food to become waste-management and renewable-fuel experts.

What is needed, if we are going to support small farmers, is for an organization to be dedicated to implementing a large number of units. From initial discussions to full-energy generation, construction of the units has to take a matter of weeks and not years, as is common with custom units.

After the units are constructed, a supporting infrastructure has to be available, including central laboratories and traveling, trouble-shooting engineers. Presently, those aspects of the technology do not exist.

Everyone who thought he/she had a good and unique idea markets it to the farmer, tries to build it, and when the final payment is made, the farmer is left with a complicated technology that may or may not operate.

I have a contractor friend who has a special term for the kind of delivery that occurs today on many farm digesters – they come with a "tail-light guarantee". That is, the system is guaranteed to work as long as you can see the taillights of the contractor.

The second strong qualifier that I added when promoting the technology, was that there were very few instances where a simple digester system alone should be adopted on farms.

In general, anaerobic digestion of animal wastes is the most cost-effective odor-control strategy and should be considered where a farmer has a serious odor problem. Animal-production farmers are in the business of dirty water management. If they are handling 100 units of animal waste (dirty water) without any waste treatment, they will still be handling 95 units after installing an anaerobic digester system, albeit a little less odorous.

Beginning in late 1990s, I wondered if it was possible to alter drastically the energy/economic/waste management situations on dairies by taking a very different approach. Putting technologies on farms, like digesters, that essentially left the waste management problem relatively the same, and greatly increased the farmers' financial and work burden, made no sense. If we were going to go down that road, we had to think in very different terms.

My vision was to take advantage of digester technology, but to use a system that completely eliminated all the wastes and created by-products that had the potential to make farming more pleasant and profitable. This meant that long-term problems, such as water and nutrient management, had to be solved. If dirty water was a problem, how could it be eliminated?

Engineers have spent decades trying to remove water from complex organics such as animal wastes using complex, inefficient, and expensive technologies. Digested dairy manure is a complex mixture of organics, dissolved salts, and microorganisms. Traditional dewatering uses high-pressure presses and screens, none of which are efficient, and certainly do not eliminate the problem. In fact, they often take one problem and make two – a wet solids cake and highly contaminated water.

Another major and well-known barrier in animal waste management is the large amount of nutrients, especially nitrogen, that are lost at rates that mitigate its benefits as a useful fertilizer, prior to returning it to the fields. Of course, even if solids could be separated from the water, it would leave sludge composed of 80+ percent water. Whole research careers have been spent developing ways of drying sludge, and none of the processes are energy efficient or cost effective.

The problem with digester effluents, I reasoned, was that squeezing water or filtering water was made nearly impossible because of slimy bacteria in manure mixtures. Bacteria are like small plastic bags of water that just aggravate pressing and filter processes by blocking water movement. We had shown in earlier work that if the bacteria were washed from mixtures of particulates and dissolved salts, the remaining undigested particulates (which represented essentially purified particles that were high in lignin content and not converted during anaerobic digestion) were extremely easy to dewater and manage. This processing of wet solids is known as "elutriation" and is not very popular because of the large quantity of highly contaminated water that is generated as a by-product. Adding large quantities of water to digested manure would seem to be going backwards in waste management philosophy, but it was one obvious way to separate particulates from the rest of the complex wet mass.

One of the characteristics of any biological fermentation is that it synthesizes significant quantities of new microbial cells – organic matter that is largely protein (greater than 70% of the dry weight). For every unit mass of organic matter converted to methane, fifteen percent is converted to new high-protein cell mass. As one contemplates that manure is 94+ percent water, contains dissolved salts, includes toxic levels of ammonia nitrogen and synthesized protein, completely eliminating digested manure is an interesting but idealistic and extremely challenging goal.

I had already developed an approach with wastewater treatment that I referred to as "Resource-Recovery Waste Treatment" (*see Ecological Engineering section*). My definition was that a "waste" could be converted into clean water and other valuable by-products with minimum energy consumption and in some cases, net energy generation. The two key processes involved were converting organic matter into a substitute for natural gas via anaerobic digestion, followed by an aquatic plant process that would harvest dissolved nutrients, the effluent from which would essentially be drinking water. The hydroponic process that I chose to develop is referred to as the "Nutrient Film Technique" (NFT), which uses plants growing in channels without root media.

With nutrient concentrations far above acceptable hydroponic concentrations, how could the NFT function with something as concentrated as digested cow manure? The answer was that dilution would be required if this process was to function.

Here were all the pieces that would "eliminate" animal wastes and convert all "wastes" into useful and potentially valuable by-products. But, how would one put them together in a practical and functioning manner? Putting the system on paper showed several possibilities. Knowing nutrient loadings that would remove 100 percent of plant nutrients as developed in the sewage treatment research, it was possible to estimate the size required to completely recover all plant nutrients. Of course, this meant that the plant system would have to be designed to remove all nutrients in a closed system, with no discharge [Fig. 22].

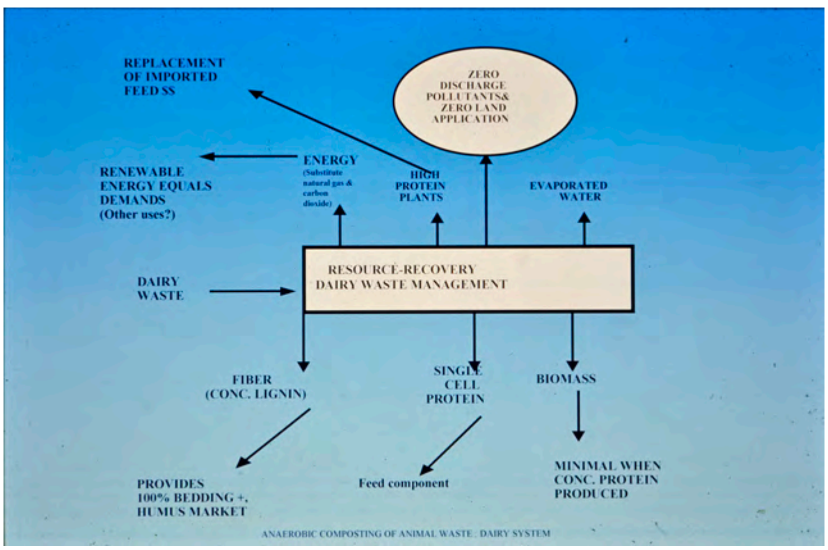


Figure 22. Illustration of components in a resource-recovery dairy-waste treatment system. Note that dairy manure and wastewaters are introduced and only useful and valuable by-products result.

A pilot system was constructed where dairy cow manure was digested as the feed to the system. As a control, and in order to evaluate the usefulness of this step in animal waste resource-recovery, raw manure was also used in some studies.

The digested effluent was diluted and a continuous gentle up-flow washing technique was used that kept particulates from overflowing while soluble salts and fine particulates, mainly microbes, were washed into the hydroponic feed tank. Aquatic-plant hydroponic units were fed from the feed tank. The treated effluent from the hydroponic units was then returned to the feed tank. At appropriate loading rates, which enabled most of the nutrients to be absorbed by the plants, the return flow essentially acted as dilution water to make the elutriated feed acceptable to the plants. This eliminated the need for additional water to be required for elutration of the digested manure.

Initially, two aspects of this closed hydroponic system were obviously problematic. Without a discharge and with constant feeding of a matter high in dissolved salts, eventually total dissolved salts would accumulate and inhibit plant growth. Second, another accumulating by-product was the extremely dark humic color that is present in digested wastes, products of general "browning reactions".

The final aspect of this system that needed to be defined was a way to convert the separated digested particles from wet slurry into a dryer product that could easily be stored and handled, and perhaps enter markets as peat moss. Although particles could be easily dewatered after the fines were removed via elutriation, the product would be too wet, and drying the product using conventional technologies would be expensive and energy-consuming. A minimal energy approach was necessary to continue to support the resource-recovery concept.

Much ambient air-drying had shown that any degree of dryness could be achieved with complex organics. However, the limiting factor was the interfacial surface area that slowly moving air could penetrate without significant management. Dewatered solids have minimal surface area and therefore are not easily dried using ambient air. I reasoned that at some moisture content, a void space would be created that would result in an interfacial surface area that would in turn support natural diffusion of water vapor from the wet particulates into ambient air. Subsequent experiments showed that dry matter content that would support natural evaporation in a solid mixture was around 40 percent.

At this concentration, water would diffuse through 3 to 5 centimeters of uncompacted material, and the digested solids could be dried by gently moving ambient air across the surface to as high as 90% dry matter. However, this turned out to be too dry, as the material became dusty and difficult to handle. Elutriated manure solids, air dried to 50 percent moisture, appeared to be close to the optimum for handling and storage.

So, how could a digested and elutriated particle that has less than 40 percent dry matter be achieved in an ambient air-drying step, especially since it is generated with dry matter between 10 and 20 percent dry? Simple - recycle the dry solids' effluent to achieve the required influent concentration.

In order to consume nutrients in a small hydroponic surface-area plant, growth rates and yield would have to be very high. Again, background with the sewage pilot system showed that continuously available nutrients, and good water quality, resulted in plant yields in excess of 100 dry metric tons per hectare per year.

Several years of operation of the pilot system showed that the hypothesized system worked to our best estimates. Accumulating dissolved salts were, surprisingly, not a problem. Overall, nutrients (both trace and macro) were taken up at rates slightly less than those added to the system in the elutriated water. In addition, the strong color did not accumulate, but appeared to be either degraded or precipitated on the plant roots. Evaporation rates were such that all excess water was removed from the system with no discharge. During extremely warm and dry periods, water was added to the system to compensate for evaporation.

After several years of testing, a resource-recovery system was capable of providing all the energy required by the farm and, in addition, a peat-moss-like product became available without significant energy input for dewatering or drying. Furthermore, a plant by-product could be available from the hydroponic system. The aquatic plant system that absorbed all the remaining nutrients represented only a small percentage of the crop area of the farm that adopted this system.

This last part of the system represented the weakest component because cattails and other aquatic plants have little feed value. What was needed was a more valuable plant that would have a higher feed value but also would grow fast enough to remove nutrients in a small surface area. During sewage studies, we noticed that duckweed (*Lemna minor*) covered the water surface whenever we gave it a chance to grow. Separate control channels had documented characteristics of this small plant.

Duckweed is one of the most interesting plants for a number of reasons:

- its maximum growth rate supports a doubling plant mass in less than three days;
- it has one of the highest protein contents in the plant world (greater than 60% of its dry mass);
- it is easily harvested, as it can be skimmed from the water surface (it looks like clover floating on water); and
- a growing body of literature has shown that duckweed has one of the highest protein feed values of any plant. It can replace soybean meal and fishmeal in diets of beef, swine, poultry, and baby pigs, as well as in aquaculture food.

Duckweed production rates appeared to be sufficient to replace all imported high-quality feed protein on dairies. This represented the last step to showing that wastes could be completely eliminated and in their place, a number of valuable by-products, such as high-quality protein, were produced.

Remaining steps to document this most valuable step in resource-recovery are to define the engineering needed to manage the duckweed, to harvest it, and to incorporate it into the feed system.

IV. Ecological Engineering

"Ecological Engineering" is the language of sustainability. When I began my career, such a term did not exist. I was an unusually educated Environmental Engineer in that I had considerably more biological and plant-based education than most environmental engineers with a Civil Engineering background. For example, I was the only engineer to spend a summer at Stanford's marine station studying algae; one of the most interesting courses for my Ph.D. was Ecological Algal Physiology. And my post-doc was with a world-renowned algal physiologist at the University of London, Professor G. E. Fogg, who was also Vice Provost of Westfield College, a division of the University of London.

IV. A. Fate of Algae, Nutrients, and Natural Systems

When I started my research, some commonly held biological concepts were not even part of our vocabulary. Much of the literature and general policy-making assumed that natural organic matter, like algae, was completely biodegraded and that natural decomposition occurred fairly rapidly. During this assumed complete degradation, 100% of nutrients would be released into the water. However, there was obvious evidence that plant matter did not disappear rapidly in a number of environments, plant organic matter that formed the basis of organics in topsoil, for example.

Cornell's famous microbial ecologist, Professor Martin Alexander, had coined a term to describe plant matter that resisted decay as being "refractory organic matter". This concept applies to all living processes and it controls important aspects of life, such as nutrient cycling in natural water and soil environments, waste treatment processes, and description of energy flows in all natural systems. As a result of the basic nature of my research, my work on algae resulted in important insight and applications throughout my career. In fact, one of the last and largest pieces of research was to describe the fate of nutrients in wetlands. I called my approach a "litter model", and it totally depended on information and concepts developed forty years earlier in my Ph.D. dissertation.

Environmental engineers were aware of "refractory organics", since a great deal of effort had been devoted to reducing sewage "sludge" by various processes. A "rule of thumb" assumption was that about 80 percent of a microbial cell was biodegradable and the remaining material resisted decay for relatively long periods, i.e., weeks or months. With this background, my Ph.D. dissertation started to examine the fate of organic matter in micro algae in lab systems. Both pure culture and natural open cultures were examined. The natural cultures were obtained from a number of sources, the most interesting of which was getting on a police boat to collect samples in San Francisco Bay.

A story beyond the scope of this narrative is how my initial thesis draft, relatively uncreative and nearly 800 pages, became quite creative and was eventually reduced to a little over 300 pages. Because my research was a federally funded effort, my dissertation also became the final report for that three-year research study.

The surprising outcome of my Ph.D. work was that, at least under aerobic conditions, micro algae had very large refractory fractions. Although my attempts to define algal refractory fraction, and conditions that might alter its biodegradability, were relatively crude, it appeared that this material completely resisted decomposition for several years. Implications for recycling of nutrients in nature were very significant.

One of my greatest regrets in my Ph.D. research efforts related to the manner in which my work ended at Stanford. My advisor, Professor Perry McCarty was very busy and occupied with a number of other Ph.D. students who focused on areas in which he was an expert, anaerobic digestion. As a result I was pretty independent to the end of the study. As I was cleaning up the lab and getting ready to leave for my post-doc position in England, I decided to dispose of all my cultures and reactors. When Prof. McCarty found out, he was pretty upset and angry. He said that he had wanted to continue some of the decay studies and that I should not have thrown them out. Several of my test systems that were destroyed had been on-going for over 600 days. This was an important lesson in communication for me and made me not take anything for granted with my future graduate students. I have always carried guilt and regret for that mistake on my part.

Perhaps as important as the general definition of refractory matter, was defining the fate of nutrients absorbed into growing algal cells. Obviously, some fraction of nutrients taken up by the algae would be released, i.e., mobilized, while some would be stored in the refractory material, i.e., immobilized nutrients. Although a fraction of the cells naturally respire, the bulk of the material enters a microbial decay cycle. As such, the microbes undergo the same division as all other material, i.e., a fraction is biodegradable while some resists decay, or is refractory. Because of environmental engineers' interest in biological processes, this cycle was well known. Unlike algae and plant materials that can store nutrients, however, most microbes have a fixed requirement. Interest is usually focused on nitrogen and phosphorus, so that became my focus.

The results of my modeling effort showed that one could predict the kinetics of decay and the fate of major nutrients in most biological systems, including natural systems like wetlands. This was the first successful effort to describe the fate of nutrients in both man-made and natural systems.

IV. B. Fate of Aquatic Weeds, Nutrients, and Natural Systems

A natural extension of my work was to repeat the effort under anaerobic conditions. Edward Foree, a Ph.D. student one year behind me, did that work. This was an interesting test of my concept of nutrient cycling, as the model took into account different microbial yields. Since anaerobic microbial yields are one-third or less that of aerobic yields, this was a challenging test. Basically, my hypothesized models applied to anaerobic conditions, confirming their validity under a wide range of environmental conditions.

One of the greatest compliments given to me for my Ph.D. work was in the spring of 1973, when I was interviewed for the position in Agricultural Engineering. After I was offered the position, Professor Alexander told me that he would have liked me to interview for a faculty position with his large research group in the Agronomy Department.

In another occurrence, while walking across the campus of Cornell University, and some 35 years after my work at Stanford, I introduced myself to a much younger microbial ecologist who had recently joined Cornell's faculty. After a few moments, the young man said, "Are you the Jewell who did the work on algal decay and nutrient cycling?" To have a new Assistant Professor, outside my field, remember my work was a great compliment.

IV. C. Defining and Designing Natural Pollution Control Systems

Several intense public arguments in the Environmental Engineering discipline related to what appropriate technologies and directions the Nation should pursue for wastewater control. One of the largest public-spending programs in history built many community wastewater treatment systems. During that spending spree, engineers argued vehemently as to whether biological, physical, or chemical technologies should be the preferred systems.

During these arguments, a number of pioneers promoted the use of natural systems [i.e., constructed wetlands] to assimilate wastes, systems that did not require any of the concrete and steel used in billions of dollars' worth of existing sewage treatment systems. The irritating issue, at least to the "treat and discharge" engineers, was the claim that the "ecological" alternatives were much more efficient and much less costly than the conventional concrete and steel solutions.

Since most environmental engineers involved in designing and building waste management facilities had little biological background, and almost no natural-systems education or experience, suggestions that natural systems, i.e., mainly land treatment, could compete was anathema. Intense and sometimes insulting discussions appeared in environmental engineering literature related to that discussion.

As the economic and efficiency arguments became well-supported, the US EPA took the unusual position of demanding that sustainable natural systems should become the "norm" and the standard against which traditional "treatment and discharge" technologies should be judged. Because land treatment systems had no discernible discharge, they became known as the "zero discharge alternative", thus creating the "discharge vs. zero discharge" policy discussion. Obviously, the "zero discharge" land treatment alternatives had a discharge, but it was to groundwater, and the quality of this discharge approached that of drinking water. Lost in the argument was that the land treatment system discharges to groundwater often reported zero pollutants, therefore suggesting purification of wastewater far exceeding the typical discharge systems.

Unfortunately, the EPA policy position occurred at a time when an insignificant number of practicing engineers had experience with natural systems. Two important events in my career caused me to begin to shift my research and teaching focus in the water purification argument. First were desperate calls from New York food processing companies, and the second was the EPA's contracting with me to define the history of "land treatment".

Many large New York food-processing companies used land application of their wastewaters as the only pollution control process. Beginning in the mid-1970s, regulatory policy insisted that these wastewaters be treated prior to application to land. This law was based on the premise that soil had little or no assimilation capacity for various pollutants such as organics, suspended solids, and nutrients. Since food-processing wastewaters carried substantial amounts of organic matter, pre-treatment meant thousands of dollars per day of added treatment costs. In addition, since these facilities were intermittently operated at highly variable loadings, the costs would be very high.

Owners of a food processing plant in central New York contacted me and asked for assistance with documenting their wastewater pollution control processes with three of their land treatment systems. Although these sites had been operating for decades, regulatory agencies had recently accused them of polluting the groundwater and demanded they install multi-million-dollar pre-treatment systems [Figs. 23 and 24].

A multi-year field effort was developed where groundwater-sampling wells were placed throughout the sites. Organic loading rates on these fields were off the chart – up to 20,000 pounds of organic matter per acre per day. To remove this amount of organic matter would have cost the food company at least $3,000 per day just in electricity.

Figure 23. Unmanaged land treatment system on the Genesse River near Rochester, New York, that caused great concern to regulatory authorities prior to Jewell's research at the site.

Figure 24. Uncontrolled "overloading" at the food-processing wastewater land treatment site showing ponding of wastewater that caused concern that it was contaminating groundwater.

Figure 25. Example of unmangaged vegetation at New York food processing wastewater land treatment site.

By comprehensively monitoring the sites, I found that not only was the grass and soil system removing most of the organic matter, it was doing so much more efficiently than any other system [Figs. 25 and 26]. In addition, even though nitrogen loadings were exceptionally high, very little was reaching the groundwater only a few feet below the grass surface. Subsequent analyses confirmed that heavy organic loadings and intermittent dosage resulted in complete nitrification followed by denitrification, i.e., conversion of all nitrogen to nitrogen gas, N_2 [Fig. 27].

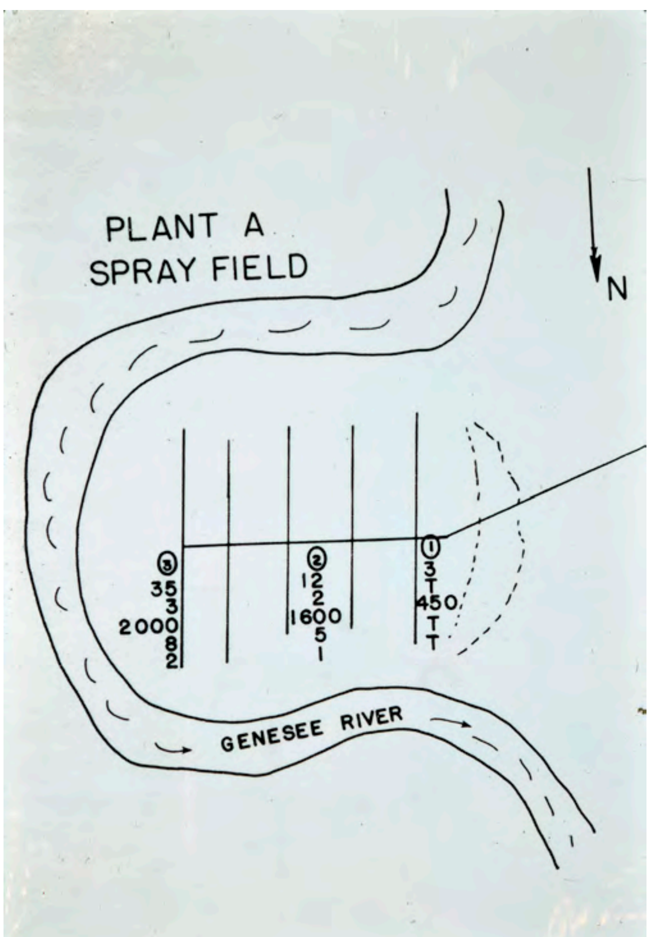


Figure 26. Average groundwater quality under the "poorly managed" food-processing wastewater land treatment site, emphasizing the huge capabilities of natural systems to purify wastewater under extreme loading conditions. Values from top to bottom are: total COD [chemical oxygen demand], BOD_5 [five-day biochemical oxygen demand], TDS [total dissolved salts], chlorides [Cl^-], NO_3-N [nitrate nitrogen], and NH_3-N [ammonia nitrogen]. All pollutants were removed by over 99%.

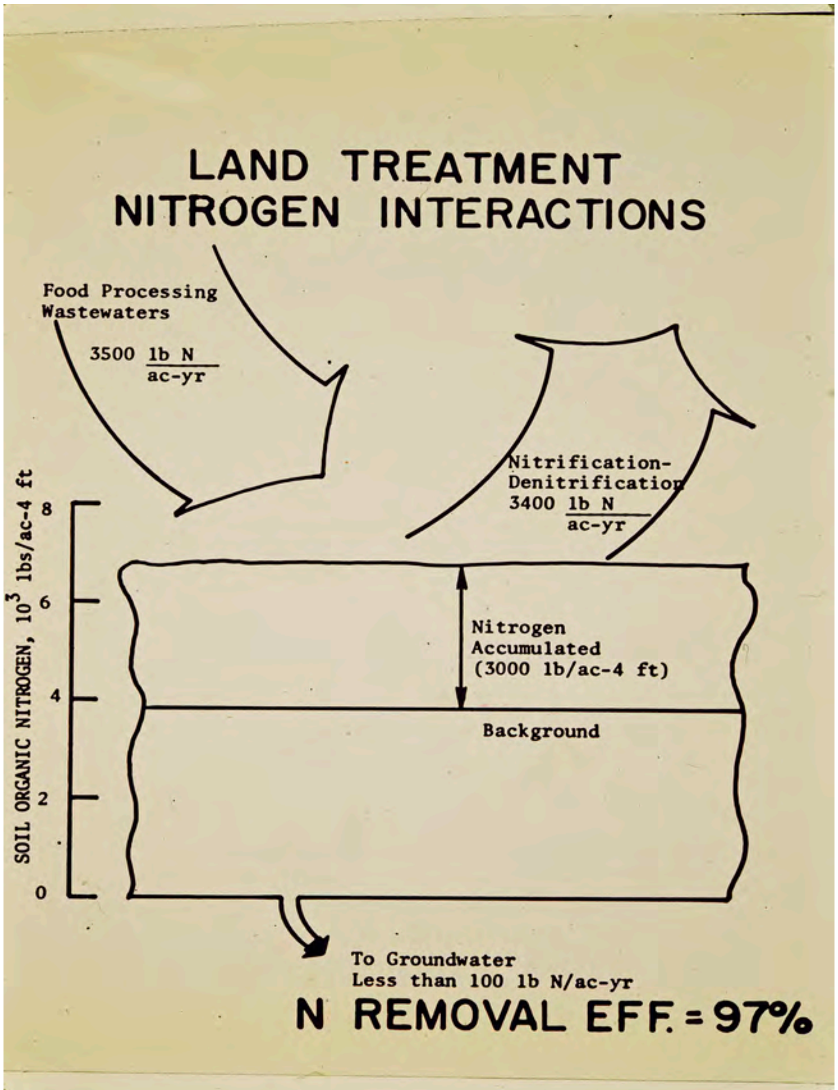


Figure 27. Mass flow of nitrogen in the New York food-processing land treatment system, showing exceptional elimination of nitrogen in this relatively unmanaged wastewater control system.

Figure 28. Aerial photo of one of two sewage treatment facilities at Springfield, IL, with wastewater flow rates greater than 50 million gallons per day that used land treatment for the treatment and final disposal of all sewage sludge.

In Springfield, Illinois, I located a system that provided corroborating data to support the remarkable capabilities of soil systems for long-term treatment of waste organics [Figs. 28 and 29]. I asked if I could visit the site to document possible ground-water contamination. They were reluctant to let any outsider see the system because they used extremely high organic loadings onto fields and felt it violated most regulatory concerns regarding sludge disposal on land.

Figure 29. Sludge applied at Springfield, IL, land treatment sites.

Theirs was a highly innovative system that was developed by an engineering company without any research support. Anaerobically digested sludge was applied to the land at rates that resulted in tons of organic matter and more than 1,000 pounds of ammonia-nitrogen per acre per year. At the time I visited the system, it had received over 20 feet of digester sludge over a decade of application. Groundwater contamination was prevented by the location of unique wells that skimmed and returned the groundwater to the sewage treatment facility [Fig. 30].

Figure 30. Return flow groundwater from Springfield, IL, sludge treatment sites. Note the extremely high water quality that results from this "natural sludge treatment" option. Total costs of sewage sludge management using this natural system was less than one percent of alternative sludge management options.

A review of the system and their data showed a noteworthy, "break-through" kind of system that used natural processes to protect the environment. The groundwater was essentially the "return" flow from the sludge, and it contained almost no contamination, even though the sludge had large quantities of organic matter, nutrients, and heavy metals. Estimated total cost of the sludge treatment and disposal was less than one dollar per ton processed. For this 100+ million gallon per day sewage treatment system, it appeared that they had saved millions of dollars using a natural processing system.

The surprising data from my food-processing studies not only assisted policy makers in adopting realistic pre-treatment regulations for soil treatment systems, it also provided significant insight into other potential applications of natural systems. In particular, one sewage sludge treatment alternative, which had evolved with little supporting data and rational design understanding, was referred to as a "reed bed sludge" treatment system. Basically, a shallow lagoon was planted with reeds. Sewage sludge was intermittently added to the bed. Any discharge was returned to the treatment facility for further processing. This lagoon had a very small footprint. Prior to our work on organics in soil systems, there was very little data to support pollutant removal mechanisms in such natural systems.

IV. D. Developing Design and Educational Bases for Natural Pollution Control Systems

The US EPA was deeply involved in policies regarding natural systems, and as such, they were aware of the lack of information and education relating to natural pollution-control systems. We were fortunate to receive support from them to develop an educational program that bridged the gap between possible ecologically designed systems and existing practices. The overall goal of that multi-disciplinary project was to synthesize existing information, develop an innovative and rational design approach, and put it into a training program for practicing engineers.

Over a three-year period, I led a large team effort that developed a design approach based on natural limiting factors. Our approach also showed how engineers could judge "safety factors" for natural systems, the same as they would for conventional concrete and steel systems. The training program that evolved was a self-paced teaching program that included hundreds of slides and narrative documentation. Eventually a two-volume textbook was published to support the program. My team traveled throughout the U.S. and ran one- and two-week training courses for the EPA in ten different locations. The US EPA officials who supported this project also participated in this educational effort.

IV. E. Introduction to Resource-Recovery Waste Management

Some would say there is no such thing as "wastes", there are just resources out of place. Finding solutions that convert wastes into valuable products is the way of the future. There is no "place" left to dispose of unwanted materials, and economics, especially in small farms, demands that these solutions be cost-effective. It is difficult to envision being able to convert completely sewage and animal wastes into desirable and useful products, but that is exactly what a resource-recovery approach must accomplish [Fig. 31].

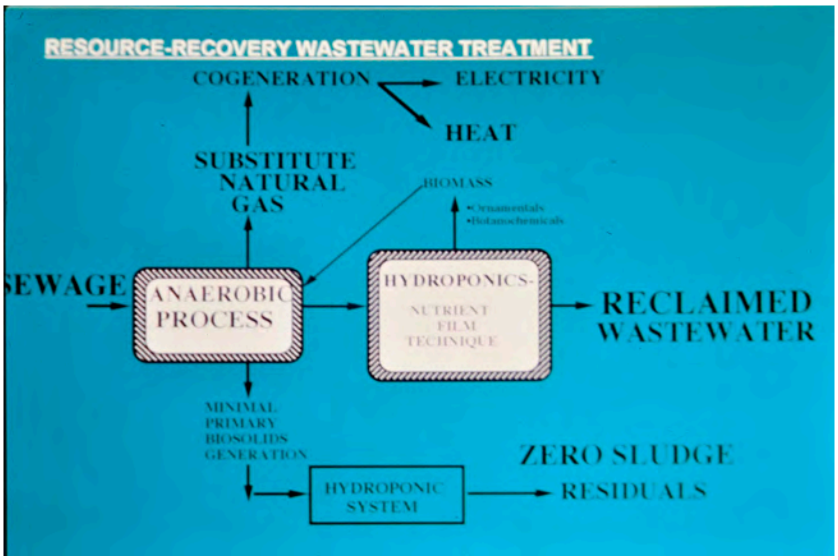


Figure 31. Conceptual diagram of resource-recovery wastewater treatment that converts all wastes into useful products without any residual production.

Anaerobic methane fermentation is an obvious component of this system, as it is highly selective in removing only carbon as well as deodorizing waste to support downstream processes. I often emphasized that anyone interested in anaerobic processes must pay careful attention to sulfur compounds in order for biological energy recovery to be successful.

The good and the bad about anaerobic digestion is that it has a very low sludge yield. As a result, all nutrients contained in the waste stream are present in digester effluents, and some, like ammonia-nitrogen, may be significantly increased via mobilization processes. Plant nutrients must be conserved, removed, and/or converted into useful by-products.

The greatest economic impact from nutrient conversion and by-product production is the growth of plants that contain valuable drugs or "botanochemicals". In descending economic order, after botanochemicals are ornamentals, structural plants, food, energy, and finally, development of wildlife habitat. The lowest-value plant purification system is perhaps the most common today – constructed wetlands for wastewater treatment.

I criticize wetland systems because they may not provide a complete accounting of pollutants, and by-product values are low. For this reason, I sought an alternative that would harvest plant nutrients in a highly contained manner and in the smallest area. In the 1970s, the "Glasshouse Research Institute" in England developed a very promising hydroponic alternative that fit these conditions. They referred to it as the "Nutrient Film Technique" or NFT. It used an impermeable surface that encouraged root mass to accumulate and serve as a solar-powered water filter for a thin film of water that was introduced to the root system.

A requirement of a new plant system was that it would have to be much more efficient than competing sewage farming alternatives and better than constructed wetlands. Our work on NFT waste applications began after I reviewed the NFT system at the Plymouth Polytechnic Institute in England. Initial work with the process began with small controlled channels in a campus greenhouse. Our focus was to determine whether an intensely loaded mono crop, such as reed canary grass, could convert organic matter and suspended solids at a rate that would make the process attention-grabbing. We also introduced cadmium to the synthetic sewage in order to determine its fate in the plant matter. This system worked well and provided the basis for further testing at pilot scale.

In 1979, we received funding from the US EPA for a feasibility study to build a greenhouse at Hanover, New Hampshire. The facility operated with minimally treated sewage (primarily settled sewage). Our main goal was to examine the possibility of growing plants – including roses, carnations, and chrysanthemums – that would provide significant income. We also examined food products, such as cucumbers. I suspected that the health of the plants would be related in some way to water purity, and we quantified this in a crude way by placing sample plants at various locations in the channels – the further down the channel, the cleaner the water.

This project was impressive in a number of positive and negative ways. Roses did exceptionally well. We had an open house and when visitors saw roses growing on sewage, a number said that we were faking the results, as it would not be possible to achieve the results we were showing.

Many of the plants, especially cucumbers and carnations, initially grew for a short period and formed fairly large root systems; however, the roots were eventually attacked by microbes and were completely destroyed.

We continued to work on the NFT for the next fifteen years, but never received sufficient support to define the fundamental limitations of the process in order to grow more valuable plants. Most of our focus was on obtaining high plant biomass yields and defining the kinetics of pollutant removal in the process.

Today, that area remains a highly fertile topic, pardon the pun.

IV. F. Introduction to Sewage Treatment with Resource-Recovery Concept

One of the important lessons learned during early testing with a highly innovative concept, such as an NFT, was that it took strong and nearly heroic persons to support funding of such efforts [Fig. 32]. Individuals who provided large funding for our studies had to withstand constant criticism from colleagues and superiors within funding agencies. They used their agencies' limited funds to pursue truly new concepts, and as a result, they received tremendous pressures both internally and externally to justify their actions. Throughout our development of the NFT, we were constantly aware that our funding was tenuous and that our sponsors were being criticized for supporting our work.

Figure 32. Mr. James Basilico, US EPA's project manager for part of the resource-recovery wastewater treatment research project. Traditional government and industry support of highly innovative fundamental research is extremely difficult to obtain and requires brave and supportive project managers to withstand criticism of agency mission supporters.

This was true from the start, even though I included as large a funding source base as could be imagined, with lead funding not only provided by the US EPA, but also from the U.S. Army Corps of Engineers, the Department of Interior Water Resources Division, the New York State Energy Research and Development Agency, and the Gas Research Institute.

I considered our funding project managers to be some of the real heroes who assisted in making real progress in research. Mr. James Basilico of the US EPA, R&D division in Washington, D.C., and Dr. H. Ronald Isaacson of the Gas Research Institute, stand out as being responsible for enabling us to proceed for a number of years.

Conversely, other individuals in these organizations, either via incompetence or intention, can be responsible for barriers and roadblocks that prevent brilliant ideas from ever seeing the light of day. These individuals occupy a special place in my mind, and remain nameless.

Our first and largest funded project was aimed at piloting the total resource-recovery concept at Ithaca's wastewater treatment plant [Figs. 33 and 34]. We designed a system to divert raw sewage at a flow rate of 40 m^3/day (10,000 gallons per day). The system was intended to eliminate many processes in conventional sewage treatment, while also demonstrating that useful products could be generated. Sewage received no pretreatment, as in sedimentation, but was treated in a two-stage anaerobic expanded bed. Effluent from the energy-production step were fed to NFT units. Unprotected outside channels were included along most of the test units inside an unheated greenhouse. Our goal was to show that even in Ithaca, minimal energy was required to use plants to purify wastewater to drinking-water standards on a year-round basis, that valuable by-products could be generated, and that energy could be generated – pretty ambitious!

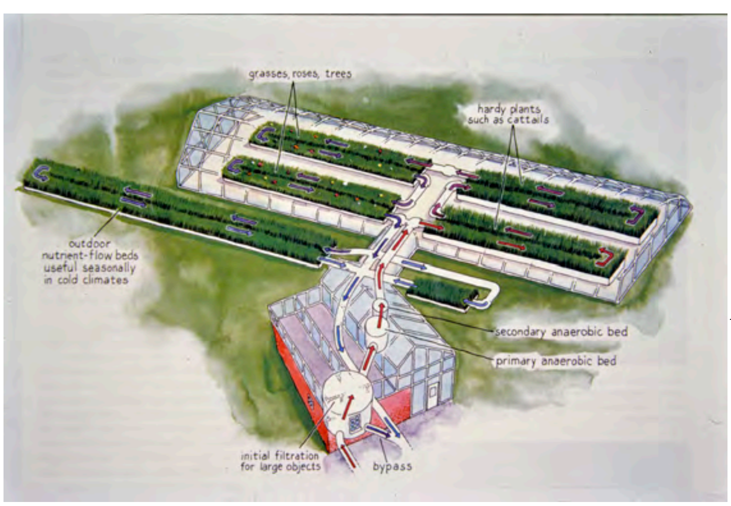


Figure 33. Schematic of resource-recovery wastewater treatment system designed to test various loadings at different levels of sewage treatment at the Ithaca Wastewater Treatment Facility. Most test flow rates were in the 10,000-gallon per day rate. The test facility used an unheated green house for the bulk of the test units, but one system was left uncovered to test freezing impact on NFT.

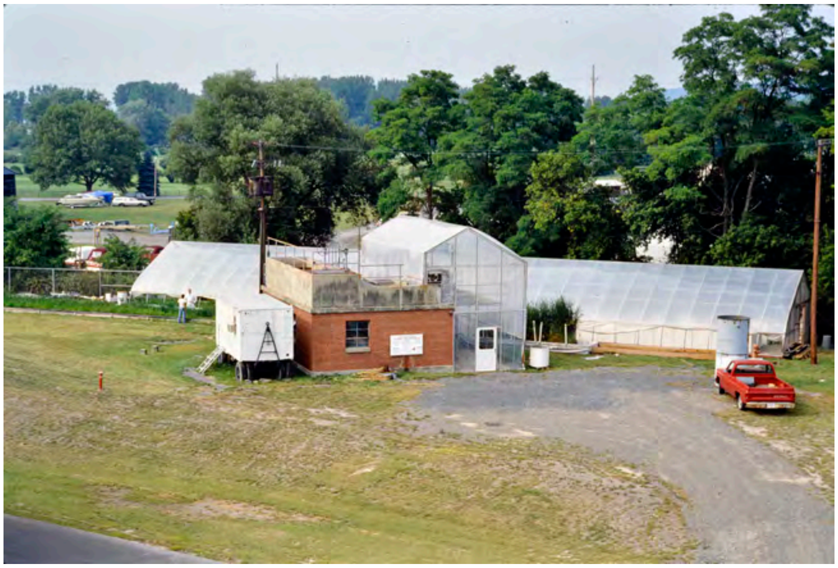


Figure 34. Photograph of Jewell's Resource-Recovery wastewater treatment pilot system, including unheated greenhouse and outside NFT treatment system, and a two-stage AFEB reactor treating raw, unsettled sewage.

That pilot system operated for four years with no interruption in flow. Several surprising observations occurred that taught us a great deal about a living-system wastewater treatment. We had chosen a local, wild species of cattails, *Typha glauca*, because of its large size and robust existence in wild monoculture. This species was also tested in Hanover, NH, and happily grew year-round inside a greenhouse. When days began to shorten in Ithaca, all of the cattails in our large channels started to go dormant and turn brown. Our wild cattails had a light-detecting gene that caused them to go into senescence, unlike the variety we chose for testing in New Hampshire.

We were devastated, since this suggested that the system would not operate year-round in cold climates. We continued feeding and monitoring the system, and throughout the four-year test program the system would die back, but the water quality did not vary; it continued to achieve excellent effluent quality. In many cases, plant nutrients continued to be removed in senescent plants to undetectable concentrations. This seemed to be a contradiction in our understanding of the plant-driven process, so we ran many side experiments to define the mechanism(s) that might have been responsible for nutrient removal. It wasn't until we had all four years of data in front of us that we were able to understand what was occurring in the system. How could nutrients be efficiently removed from wastewater even when plants were not growing? Solving this mystery required incorporating information from my Ph.D. dissertation, and it explained many other natural processes.

The second biggest surprise occurred early in the program after our cattails had grown to a magnificent 10-feet tall, or more.

One view of root accumulation on an impermeable surface quickly impresses the viewer with the potential for the NFT system to be used as a solar-powered water filter [Figs. 35 and 36]. But it also raises many questions. Could a closed greenhouse system be used as a water recovery system that would capture evaporated water? What happens to large quantities of root and upper biomass that accumulates? Does root mass become clogged and ineffective? What happens in freezing climates? These were some of the questions we tried to answer, and nearly all resulted in impressive potential for the system to be useful even in cold climates with unheated greenhouses.

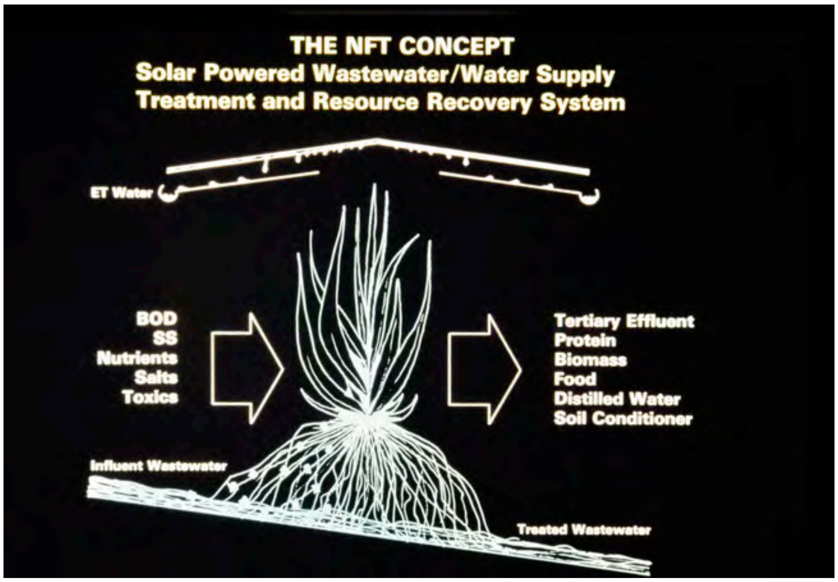


Figure 35. Conceptual diagram of the solar-powered water filter created by NFT wastewater treatment.

Figure 36. Typical root mass accumulation that forms the solar-powered water filter in an NFT [nutrient film technique] system.

It also is obvious that wastewater treatment with the NFT process requires consideration of the interactions of pollutants and plant characteristics. For example, heavy loadings of organics in sewage would cause oxygen stress on the root mass, as well as exposure to industrial pollutants such as heavy metals. Very tough plants would be required to purify heavily contaminated water. Other characteristics, such as tolerance to high dissolved salt concentrations become important. Initially, it was hypothesized that a tough plant that grows in zero-oxygen water, like swamp plants, would be required in the first treatment section [Fig. 37]. After water quality reaches a certain higher level, more sensitive and potentially valuable plants could be grown to generate more valuable by-products. Finally, plants that can tolerate extremely low nutrient concentrations would be used to "polish" wastewater to a quality approaching drinking water.

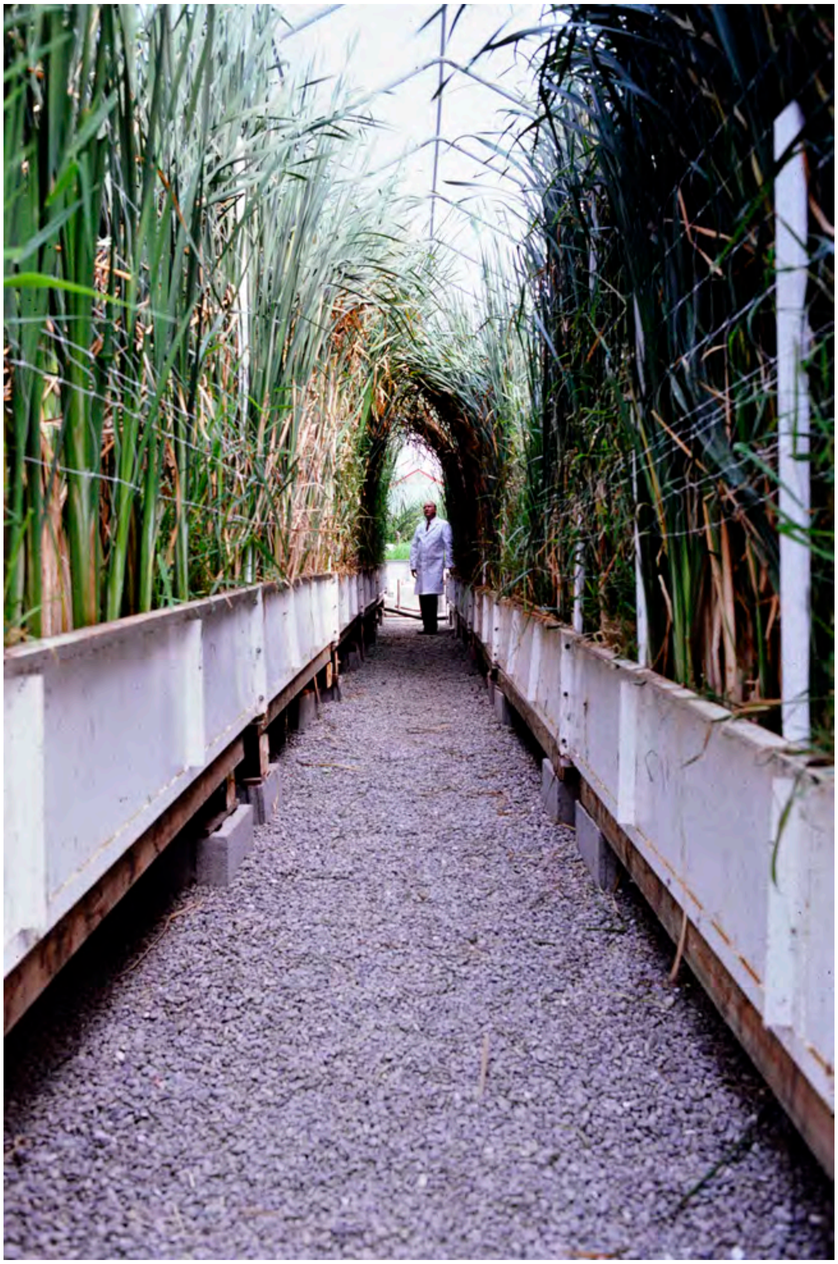


Figure 37. First stage NFT system using cattails [Typha glauca] *to treat wastewater following anaerobic treatment of raw sewage, with the AFEB unit showing the size of cattails with Professor Jewell at the entrance to the channels.*

Most of our work focused on one plant, a large local cattail [*Typha glauca*], but many others received attention including roses and food plants [Figs. 38, 39, and 40]. Plant nutrient rich wastewaters stimulated extremely high yields in NFT channels, as well as very large root accumulations.

Figure 38. One of the important characteristics of NFT plant treatment of wastewater was the exceptional effluent quality. Prof. Jewell holds influent raw sewage in his right hand and effluent in his left hand. Note that the beaker has numbers next to his hand emphasizing clarity of treated water.

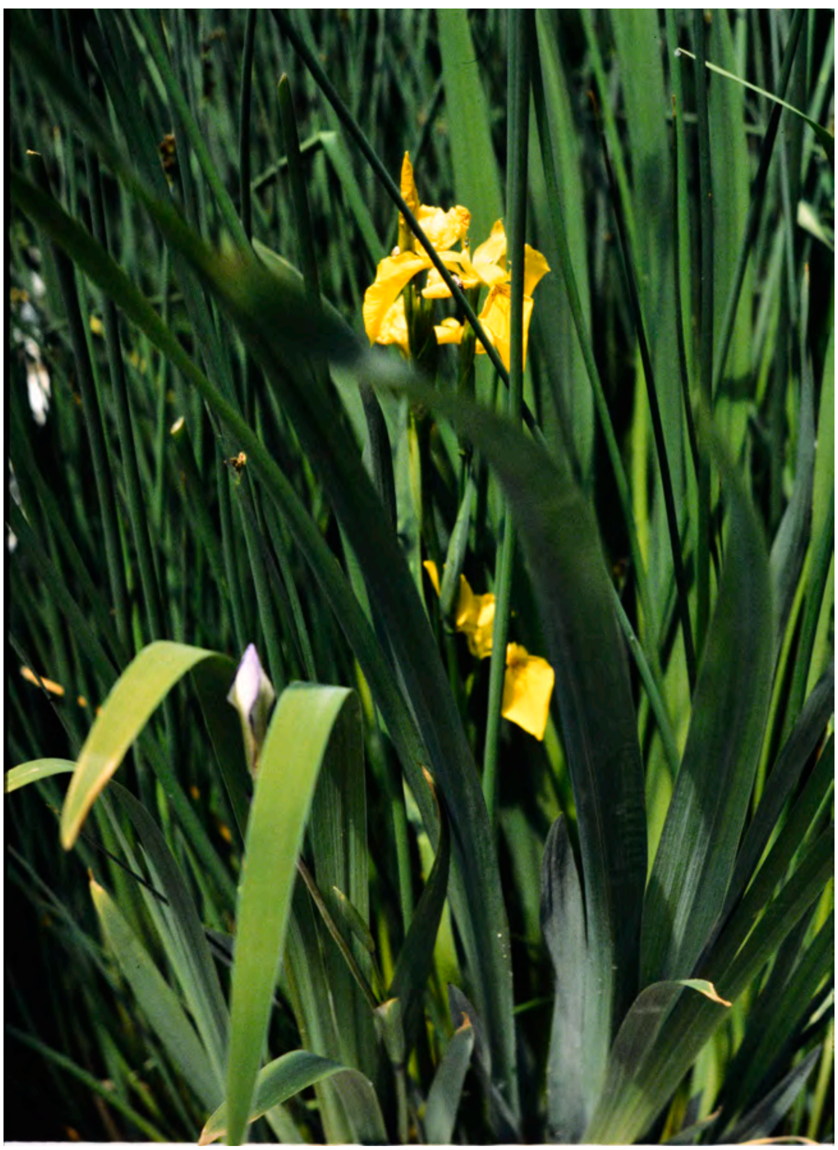


Figure 39. Cut flower production in the NFT treatment of sewage represents one option for income generation. Other options that would generate significant revenue include botanochemical plant production.

Figure 40. Alternative plants were tested in the sewage treatment NFT, including this subsample of Elephant grass [Napier sp.] *obtained from a wild sample in Florida. Plant biomass yields exceeded 100 dry mt/ha-yr with several grasses.*

Figure 41. Outdoor NFT designed to treat 1,000 gallons per day of raw domestic sewage, in early growth stage. All plants in this test were wildlife food options. Note low nutrient stress caused smaller plants as well as a lighter green, indicating low nitrogen availability as the water quality increased from left to right.

Figure 42. Outdoor NFT designed to treat 1,000 gallons per day of raw domestic sewage. Influent is on the right. Effluent on the left approached drinking water quality. Note the lush green color at the influent where plant nutrients are in abundance, and the faded green color denoting nutrient deficiency at the effluent water quality.

Energy consumption in wastewater treatment is one of the parameters that we wanted to minimize. As a result we tested several NFT channels outside greenhouses that were allowed to freeze [Figs. 41 and 42]. Several channels were tested with raw sewage. Many of these tests also showed great potential for simple and effective wastewater treatment.

Figure 43. Duckweed wastewater treatment channel designed to define growth characteristics of Lemna minor *in sewage treatment.*

Early in our sewage treatment, a floating nuisance plant was an unwanted invader – duckweed [Figs. 43 and 44]. Anyone who has a fishpond or free water surface is familiar with this small floating clover-like plant. In order to quantify its influence on our system, we were forced to introduce several additional channels just for duckweed measurements. This was a very fortuitous offshoot of our work, as it became an important part of animal wastes treatment systems because of its high nutritional characteristics. See more comments about this amazing plant under Resource-recovery dairy waste systems.

Figure 44. Beaker containing subsample of duckweed [Lemna minor] *emphasizing high water quality obtained with duckweed treatment of sewage, as with other macrophyte treatment with the NFT.*

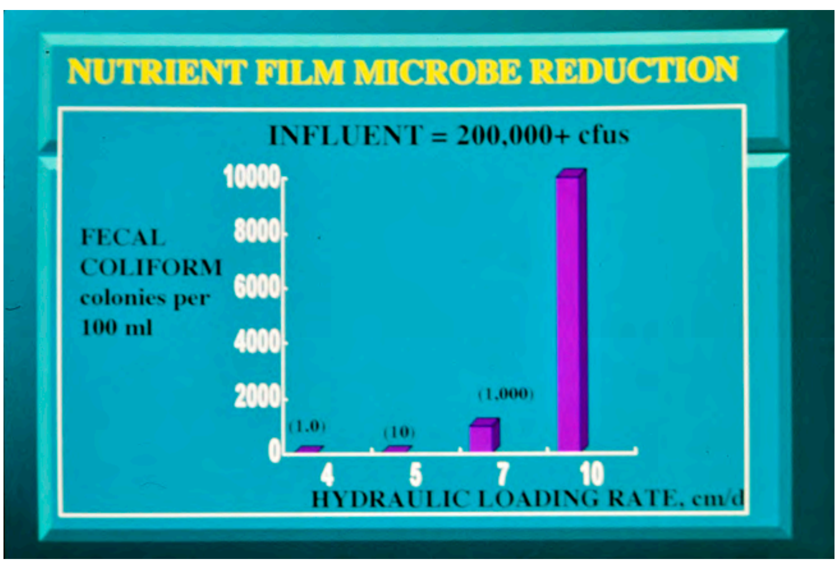


Figure 45. Bacterial indicator data from NFT sewage treatment. Although most natural plant purification systems are not capable of reducing bacteria to drinking water quality, the NFT system was able to achieve undetectable indicator organism concentrations at low hydraulic loading rates.

Our greenhouses were as complex a closed ecosystem as one could imagine. However, insects began eating our cattails. This was not supposed to be possible, as the cattails are not vigorously attacked in natural stands. But all over the greenhouse, spider populations were so numerous that during a walk through our channels first thing in the morning, we would have to hold our hands in front of our faces to collect massive cobwebs that had been built overnight.

To control the insects, we tried every conceivable pesticide, even lethal ones that had not been fully approved by authorities. This, of course, flew in the face of our goal of safe and low-cost ecological systems. Eventually, we stopped all pesticide treatment because none were working in arresting the death of our cattail monoculture. Only about 25 percent of the cattails remained in early testing and they were a real mess! We initially, very reluctantly, concluded that if insects could decimate this system, then it would not be worth developing.

Our final attempt to control insect pests was to bring in a commercial integrated pest management expert (IPM, Inc. of Locke, NY) [Fig. 46]. By introducing insects that preyed on those killing the cattails, we were able to control all destruction. From that point on, integrated pest management was a key to maintaining a thriving plant population inside the rich greenhouse environment. Our work also defined the cost of such management, estimated to be around $15 per acre of greenhouse per year, a very reasonable amount.

Figure 46. NFT treatment of sewage results in an extremely rich biological environment that supported many pests that waged biological war on the cattail monoculture. Relatively simple and inexpensive integrated pest management was used to control all insect problems. Note the dense aphid population on the cattail blade in relation to release of "aphid lions."

As we were conducting this effort, The US EPA was developing guidelines for plant-based sewage treatment wetlands. Eventually, their design guidelines suggested that plants could be useful in removing suspended solids and organic matter (Biological Oxygen Demand, or BOD), but that they would not be used for nutrient removal.

"Plants could not be used to remove nutrients!" What nonsense was that, we thought. the US EPA experts reasoned that if plants were not harvested, just as they were not in wastewater treatment constructed wetlands, they would eventually decay and all of the nutrients initially removed would be released back into the treated water. For most of our study, remains of cattails were left to decay with only some flowers harvested.

Of course, we were concerned about sediment collection in our channels, and the requirement to account for the three-meter-high cattails and the remains of over 100 tonnes of dry matter per hectare per year. To our surprise, accumulated sediment was less than several inches per year.

The author of a primary reference source on wetlands suggested that the most important community in wetlands were "decomposers", and that they were more important in nutrient management than the plants themselves. The fate of plant matter in these systems looked a lot like my Ph.D. dissertation, so we began to construct models based on plant growth and decay, which incorporated both nutrient mobilization and immobilization components.

Comparison of the relationships between water retention times, nutrient loadings, plant yields, and decomposition were examined. Several surprises were reflected by the data. First, there was a definite relationship between loading and system-nutrient-removal efficiencies or rates. Second, no matter how hard we tried to separate temperature and plant growth effects, we could not see any influence from these parameters. Winter temperatures, where the water in the hydroponic system approached 0°C (remember, we wanted to minimize energy input so we did not heat the greenhouse except during very cold nights to prevent plant freezing), had no effect on nutrient removal aspects. Third, contrary to US EPA's design guidelines, the system was not only very efficient at removing nutrients, but also, even at low loadings, it achieved undetectable nutrient concentrations in the effluent. Results from mathematical modeling showed that incorporating microbial growth and decay aspects could predict the observed results.

Apparently, nutrient removal characteristics were driven by the microbial system. Large plant yields supported a steady-state decomposer community on a year-round basis. Temperature was not an influential variable, because the kinetics of decomposition was rate-limited by the availability of carbon coming from plant biomass. In a sense, the existing literature was correct: that plants, by themselves, do not control the picture, but their yield controls the eventual character of the system.

A review of constructed wetlands and the reported data for some systems indicated that my model for the sewage treatment pilot system also applied to wetlands. In at least one well-documented example, I was able to show that the model could predict the following characteristics of lightly loaded wetlands:

- nutrient uptake efficiencies for nitrogen and phosphorus, plant yield, and litter or decomposer debris accumulation depth; and
- litter composition in terms of nitrogen, phosphorus, ash, and organic fractions.

The fact that the model worked on wetlands that had been in operation for several decades suggested that the "refractory organic" concept can apply to natural systems for many years beyond documented tests.

Implications of these results suggest that carbon sequestration in wetlands could be an additional bonus in this age of climate change.

I emphasize that the "litter model" is essentially the same as the model developed in my Ph.D. dissertation four decades earlier. Pretty good shelf life!

IV. G. Introduction to Dairy Manure Treatment with Resource-Recovery Concept – Moving Towards Energy-Independent and Pollution-Free Farms

Extending the "Resource-Recovery approach" (i.e., both energy and by-product recovery) to dairy waste was a bigger challenge than wastewater because of large amounts of particulate matter. Background to this technology is described in more detail in the *"Energy and Agriculture" section.*

The main difference between the two is that the dilute nature of sewage makes recovery of useful by-products less attractive than possibilities presented by animal wastes. In addition, characteristics of the system enabled the ultimate goal of complete elimination of the animal waste to be achieved (because excess water is evaporated at ambient temperatures).

Although the entire manure resource-recovery system was piloted for a significant period, the last topic that I worked on, and perhaps the most important component – high-quality protein recovery – needed further development.

Two areas of protein production are potentially the most valuable component. Recovery of microbial mass, either directly or via vermiculture, can accomplish simultaneously important liquid/solid separation and by-product recovery. Duckweed production as a means to recover most ammonia-nitrogen has potential to replace the most expensive component of animal production: high-quality protein feed. Duckweed has been shown to be of sufficiently high quality that it can replace all animal feed protein additives. It would be most valuable in poultry and aquaculture feeds, because of the ramifications of its quality and the feeds that it replaces.

Evaluation of resource-recovery found that dairies could significantly reduce crop areas needed to capture all the nutrients in waste. Recovered fiber could be marketed and used as a bedding material, or conversely, used as bedding and then land-applied to support soil conditions and provide carbon sequestration – making it possible for farming to have a "negative" carbon footprint!

Economics suggest that such a system could not only eliminate all pollution and make animals much more comfortable with large quantities of pasteurized bedding materials, but it would also make farming much less dependent on energy and imported feeds, while having the additional potential to increase the economic "bottom line" of farming.

IV. H. High Solids/Anaerobic Composting Development

Figure 47. Anaerobic composting lab-scale reactors showing high solids and no liquid.

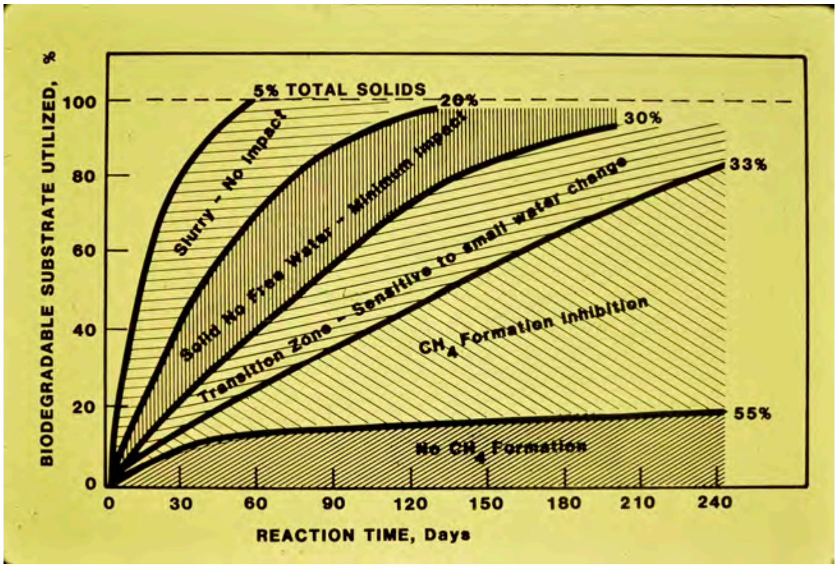


Figure 48. Fundamental relationship between anaerobic digester dry matter content and reaction rates that formed the basis for operating a high solids or anaerobic composting reactor.

We did the fundamental work to show limitations of available water on methanogenic activity [Fig. 47]. This led to new applications of anaerobic digestion of dryer materials, including straw and municipal solid wastes. Any organic material with a dry matter content below 25 to 30 percent can be unlimited in kinetics of conversion under methanogenic conditions [Fig. 48]. This leads to better understanding of kinetics in landfills and natural systems.

Figure 49. Full-scale test of anaerobic composting of straw.

IV. I. Conversion of Wood to Substitute Natural Gas

Figure 50. Handful of hybrid poplar wood chips used in test to determine the potential biodegradability in anaerobic composting.

One of the unique contributions of our team to renewable energy was our work on conversion of wood to methane in anaerobic digestion [Figs. 50, 51, and 52]. Early in the US DOE's program, research was initiated to determine the potential of wood chips to provide a biomass for renewable energy. Eventually this work has shown good potential for high wood yields on marginal lands. Our work showed that digestion could convert half or more wood biomass to substitute natural gas. In addition, the process could be envisioned to generate an enhanced lignin concentration by-product, as well as a high protein material.

Figure 51. Lab-scale tests of anaerobic digestion of hybrid poplar wood chips.

Figure 52. Pilot-scale test of anaerobic digestion of hybrid poplar wood chips.

IV. J. Study By-Products

IV. J. 1. Methanotrophs Used to Control Eutrophication

One of my five patents deals with using methane-oxidizing bacteria to control nutrients in water bodies. This concept was developed based on fundamentals of microbial growth. If one could encourage microbes to grow in any water by supplying only a carbon energy source, they would have to scavenge their environment for all other macro- and micro-nutrients. By adding relatively small quantities of natural gas to water, microbes could absorb the nutrients.

Many backyard ponds control micro algae growth using this concept – by adding straw to ponds. This stimulates microbial growth that absorbs the soluble nutrients that stimulate algae growth.

IV. J. 2. "Biodegradable Plastic Analyses" Development

One of the concrete examples of how commercial activities can benefit teaching and research experiences for students is related to a highly secretive and long-term effort to develop tests to confirm true plastic biodegradability [Fig. 53]. I headed several projects to confirm plastic biodegradability with DuPont and several larger fast food companies to document and prove whether plastics could be biodegraded by microorganisms. This protocol still stands as the most comprehensive approach to define plastic biodegradability, but would never have been published if Cornell University graduate students had not been involved.

Figure 53. Graduate student, Larry Krupp, conducting biodegradable analysis of commercially available biodegradable plastics.

Another interesting study related to long-term closed systems. This preliminary effort – supported by the Space Studies Institute at Princeton University – documented food production, energy consumption, water requirements, and waste generation and treatment in long-term closed human environments. This effort concluded that a large part of the resource-recovery approach would be useful in closed systems.

Most surprising was that the limiting aspect of the closed system was related to nitrogen interactions. Nitrogen, via a number of microbial-related reactions, would be lost to nitrogen gas; therefore, nitrogen fixation would be required to keep the system in balance over the long term.

V. Toxics – 1988-1995

My foray into toxics remediation was both fortuitous and intentional at different times. It also had a major commercial component, as did my interest in anaerobic digestion. My first effort, derived from a technology imported from Europe, was already in place when I was hired at Cornell. The second occurred when federal funding in the energy area disappeared and the country became focused on industrial toxic sites, or Superfund sites.

The expedient thing to do when your main interest is no longer a part of the national interest is to shift gears and go where new funding exists. I pursued toxics bioremediation, very successfully, until it became too uncomfortable and dangerous to my students to continue in that area [*see V.B.2*]. It was at the end of large toxics-remediation project funding that I decided to return to renewable energy and agriculture.

V. A. Autoheating Animal Waste with Air Aeration to Achieve "Liquid (Aerobic) Composting"

German and Scandinavian engineers had developed a process they referred to as "Liquid Composting", which was being marketed as an aerobic treatment system for animal wastes. Although my initial interest included aerobic treatment, it was quickly diverted because of the electricity cost required to provide oxygen for such processes. A quick review of energy costs needed to operate aerobic "Liquid Composting" systems on dairy wastes showed that it would incur electricity costs of around $1,000 per cow per year. Since the net profit to a dairy is less than half this cost under the best circumstances, it was clear that the application of this technology would not be economically attractive. This negative economic aspect just added to the challenges of this new technology.

V. B. High-Shear Field Self-Aspirating Aerators – Oxygen Transfer Efficiency Breakthrough and Foam Generation

The fundamentals of liquid auto-heating during aerobic fermentation were challenging. According to conventional wisdom, autoheating, i.e., heating of the liquid to around 50°C – without the addition of external heat energy – could not be achieved by using aerators that used ambient air. All air aerators were so inefficient that they stripped off any exothermic heat created by the biological reactions, which normally auto-heat composting reactions.

I had been involved in full-scale aerator analysis in several large consulting projects and was quite familiar with aeration and its energy profiles. I should have expected substantial differences to occur, because the German literature cited unusual aerator characteristics, and the aerator itself was extremely unusual. The six-inch square aerator (Fuchs unit) was very small to mix a ten-foot diameter tank, fourteen feet in depth. The type of aerator was self-aspirating, in that it didn't require a compressor to inject air into the liquid. Rather a vacuum, created by curved veins, sucked atmospheric air into the center of the aerator. It then flowed out to the edge of the square veins and was sheared off at the knife-edges of the square aerator. Hence, these aerators became known generically as "high-shear field" aerators. To my knowledge, there are only two such units manufactured.

V. B. 1. Full-Scale Demonstration

A full-scale manure system had been installed at our research dairy. I decided to conduct a study to determine the basis of aeration claims for the European system. Lo and behold, the system worked and autoheated manure to well above 50°C, even in the winter. The most unusual characteristic of the system was accumulation of extremely fine foam on top of the reactor. This was expected, as the system was installed with mechanical foam cutters to ensure that foam did not overflow the reaction tank. Eventually, this fine milk-shake-like foam formed the basis of important characteristics of the system. In documenting the system, we installed an *in situ*, bubble-size measuring system and found that not only were the foam bubbles exceptionally small, but they were also generated in only one size.

Another aspect of this research was to document the impact of liquid solids on the efficiency of the system. Part of aeration theory dictates that as solids' concentration in the waste increases, all air transfer efficiency decreases. Not only did oxygen transfer capabilities of the aerator exceed all other aerators, but the basic aeration theory was also invalid with these high-shear field aerators. In fact, the solids interacted with the aerator in exactly the opposite manner as theorized: as solid concentrations increased, oxygen transfer capacity of the aerator also increased, instead of decreasing as with all conventional units.

For several years, I used this example of non-conforming theory to actual experience, to show students there are limits to our theoretical knowledge. In one class, Evan Koslow, one of my most brilliant Ph.D. students, told me after class that he thought he could explain the engineering physics behind this aerator, and that he would provide a mathematical description.

The next day I found a six-page mathematical analysis of high-shear field aerators on my desk. After the first paragraph, I knew that the math was beyond my capability to understand it. When Evan came in, I said that I could not follow his explanation. In a verbal description, he basically explained that extremely high shear created by the fins at the edge of each square in the aerator, created the uniform and extremely small bubbles that we observed. In addition, he said that with a few hundred dollars of equipment and a water tank, he could demonstrate such an aerator. We scrounged the equipment together and in a few days we were set to demonstrate how high-shear fields could generate small bubbles with very little energy input – using a high-speed wood router.

When Evan turned on the unit in a glass-walled cube, containing about a cubic meter of tap water, one of the most incredible things occurred: instead of generating bubbles from the aerator, what looked like smoke began to form in the water. Bubbles were so small, and their buoyant force was so small, that they did not float to the surface but remained suspended in the water. This "high-shear field aerator" was different from anything I had ever seen or could imagine!

The German aerator, "Fuchs aerator", was the only one I had ever seen capable of creating the shear field. Sometime later, an American manufacturer marketed an aerator with similar characteristics, "Midland-Frings", and this became the aerator used in further studies.

V. B. 1. a. Pathogen Destruction

A number of topics came into play that continued to keep our interest in aerobic liquid composting. The US EPA had developed a national policy regarding final sewage sludge use and disposal – i.e., beneficial use of sludges (renamed "biosolids" by the Water Environment Federation as a PR improvement). In order for sewage sludge to be used on agricultural land, it had to meet pathogen destruction and maximum heavy metal standards. At that time, it was known that most conventional sewage treatment technologies, such as completely mixed mesophilic anaerobic digestion, did not meet pathogen destruction levels, and this was before the EPA instituted strict control over heavy-metal-containing industrial sludge. Syracuse sludge, for example, contained cadmium at 100 to 1,000 times the EPA's limitation for the use of sludge on agricultural land as fertilizer or soil enhancement.

When liquid is heated to thermophilic region, i.e., greater than 43°C, all warm-blooded pathogens are killed in a matter of hours. Since the liquid composting process required retention times in the order of days, we expected, and confirmed, that complete pathogen destruction and virus inactivation occurred. In documenting the autoheating potential and pathogen destruction, we tested tanker-truckloads of sewage sludge from a number of municipalities. This information enabled this process to become one of the US EPA-approved processes to achieve "further pathogen reduction", so that sludge could be safely used in agriculture. Several companies were formed, unrelated to me or Cornell University, to commercialize this technology.

I anticipated that our work might be used to promote the application of sewage sludge on land and began to examine my concerns about such a policy and practice. Early in this work, I prepared an overview that discouraged the use of "biosolids" in agriculture, purely from a logical standpoint.

V. B. 1. b. Heavy Metal Removal and Recovery

Sewage sludge contains much soil humus and plant nutrients as well as other materials, including toxic heavy metals. I pointed out that all sewage sludge generated in the U.S. could be used on "damaged land", and that none need be applied to food production land. Strip-mining laws, for example, require sites to be treated at the end of mining so that a perpetual plant cover would be maintained. Sewage sludge would be an excellent material to reclaim such "destroyed" land.

Dealing with pathogen destruction was pretty straightforward compared to the other common toxic problem with "biosolids" – heavy metals, mercury, cadmium, zinc, etc. Many municipalities process industrial waste and common sewage biological treatment concentrated these metals beyond what should be allowed in agricultural land. I wondered if high-temperature treatment was severe enough to enable heavy metals to be removed from these complex organics. In a brief review of the chemistry of most heavy metals, it showed that high temperature under aerobic conditions would have little effect; however, examination of redox/solubility diagrams showed exciting possibilities for toxic metal management.

Acidifying complex organics solubilized some metals; however, this solubilization process was not very efficient in many tests. What became clear was that maintaining a highly aerobic microenvironment, and subsequently acidifying this aerobic condition, solubilized nearly all the heavy metals. Increasing the temperature also assisted in their removal. Neither aeration, heat treatment, nor acidification worked alone, but in proper combination they were extremely effective. Heavy metals in contaminated sludges could be removed down to background levels, or concentrations similar to that in cow manure.

In 1985, my team developed and was eventually awarded a patent in this area. But even today, many sludge-management practitioners are not familiar with the possibilities of pathogen and heavy metal control using aerobic liquid composting and pH management.

My energy consciousness came into play here as I still felt that liquid composting was too energy-intensive to be used for sewage sludge stabilization. It would be much more beneficial if sludges could be treated with an energy-producing step, like anaerobic digestion, then treated further to kill pathogens and remove heavy metals.

We suggested that, since there were unoxidized organics remaining after digestion, then theoretically, anaerobically treated sludges could be autoheated to pathogen-killing temperatures, or, in other words, to achieve pasteurization with no heat energy added, and minimal aeration energy with hydraulic retention times of one to two days. We proved that this final deodorization and pasteurization step could easily work on common anaerobically digested sludges, thus eliminating the need for extreme energy-consuming applications. (*See comments under Commercial Activity in this area for another frustrating commercialization effort.*)

V. B. 2. Detoxification of Groundwater with Biofilm Processes – Methanogens and Methanotrophs

The most common contaminants in groundwater are the chlorinated organics – chlorinated ethenes, tetrachloroethylene (PCE), and trichloroethylene (TCE) – and their more volatile and more toxic by-products, dichloroethylene and vinyl chloride. These organic solvents had many common uses, such as in dry cleaning and metal cleaning, and prior to knowledge that such solvents are carcinogenic, they were used in many cases and indiscriminately disposed of. Once their ubiquitous nature became known, especially in drinking water, a large R&D effort was undertaken to find treatment alternatives.

We proposed that the large biofilm population in my process, anaerobic expanded beds, had the potential to remove and biodegrade these toxic organics. We also were aware of an unusual microbe that used methane as an energy source – methanotrophs – and could dechlorinate some of these toxics. As a result of our work in substitute natural gas production, we were fortunate to have the attention of the natural gas industry, and because of their interest and knowledge of our successful biofilm work, we received substantial funding to chase down those toxic materials using bioremediation.

A large multi-million-dollar effort ensued, along with a large R&D team. Within a year, it was clear that both anaerobic methanogens and aerobic methanotrophs had the potential to dechlorinate those compounds. It took another year or so to sort through the fundamentals and kinetics of microbial dechlorination.

Two of the six full-time researchers finished their Ph.D.s while working on or shortly after this project, and are now full professors [Donna Phillips at Rutgers University and Yarrow Nelson at California Polytechnic State University (Cal Poly)].

The combination anaerobic/aerobic biofilm process we developed was the first process shown to be capable of removing the chlorinated ethenes to near-undetectable levels. Our group was highly complimented when the American Chemical Society, in a widely disseminated booklet, identified our work as one of the most important research projects of 1989.

Towards the end of our contributions to this area, a number of investigators made progress on identifying organisms that were even more efficient at removing these toxic organics.

I made the decision to discontinue this work for a number of reasons, one of the most significant of which stemmed from a lab accident. While at a meeting in another building on campus, I was summoned to an emergency at my lab. When I arrived at my building I found that evacuation had been ordered and hundreds of students were milling around outside. One of my lab technicians had made a serious error. When he could not access the vinyl chloride standard gas (a pressurized metal bottle containing over a half kilogram of vinyl chloride, a highly carcinogenic gaseous chemical), he decided to take off the top with a pipe wrench. This caused the bottle to explode. Fortunately, when it exploded, he yelled: "That's vinyl chloride gas, get out!"

The senior research engineer in the lab was smart enough to hit high-volume emergency evacuation fan switches so no one was exposed to the gas, as far as I know. The thought of what possible exposures could have occurred because of this accident convinced me that no matter how much funding we received for additional toxics research, it would not be sufficient to endanger either workers or students. Someone in the private sector, who would eventually benefit from successfully applying a toxic organics removal technology, could pursue this dangerous work.

I returned to working on renewable energy and agricultural wastes.

V. B. 3. Biological Burning of Medical Wastes

My final contribution to toxics treatment was one of the most original and least expected. It was driven by the Cornell Veterinary School's problems with their medical waste incinerator. They decided to try and obtain a permit that would enable them to increase the size by rebuilding the existing medical waste incinerator. This, of course, raised many issues with the surrounding population, and it was clear that permit approval was not going to be an easy process.

I had been involved with anaerobic digestion of solid waste, as well as development of a process to define biodegradable plastics. This background enabled me to create a high temperature (60°C) biological process that could eliminate most medical waste problems while killing all pathogens. Methane generated in the process could be used to dry and/or burn any remaining residue after all toxics were reduced to humus. It was the combination of technologies that led me to suggest a completely contained method of disposing of medical wastes – "Biological Burning".

A synthetic medical waste was developed composed of whole mice, pieces of cow's tails, Petri dishes full of agar and microbial communities, feathers, cotton and plastic textiles, etc. These were prepared in such a way that they could be processed through biological fermentation and then recovered to determine the efficiency of biological destruction. After six months of operation, it was concluded that nearly all of the organic matter was converted to methane, and any remaining material was deodorized and left as a small amount of pathogen-free humus. This showed that a closed system could treat animal body parts and associated medical materials.

After over a year of testing I invited the Dean of the Vet School to review the process. He did not feel that the process was worth pursuing. Years down the road, a committee chose a multi-million-dollar alkaline liquefaction process to replace the incinerator at the Vet School. The philosophy of such a process is the old-fashioned *"dilution as the solution to pollution"* , as the liquid material is transported to the local sewage treatment facility, treated, and eventually discharged into Cayuga Lake.

It should be noted that the College of Veterinary Medicine and Biomedical Sciences at Colorado State University first adopted medical waste liquefaction in the early 1990s, and it was a failure. Problems with the process and the impact on the wastewater treatment plant resulted in abandonment of this option.

V. C. Research Overview

I loved my career in "wet" research – research that depended on carefully defined and executed experiments with living organisms from pure microbial cultures to macro plants and earth worms. Perhaps as important was the close relationships that existed between me and members of my research teams. Some of the time part of the $13 plus million dollars of outside support provided Cornell with 100% of my salary, as well as that for a full-time professional assistant. Much of the time this team consisted of more than ten full-time researchers, often including one or more postdocs. The high point of many of my days was sitting with my team during coffee breaks and listening to advances, surprises, or frustrations of the daily laboratory testing program. At one point one of my team put a Garfield joke on my door that said "What is your favorite donut? All of them!"

I always encouraged full-time researchers working on my projects to take "free" courses that Cornell built into such positions. Nothing made me more proud than to see a research technician complete a Masters or a Ph.D. while working full time.

Counter to these positive experiences, there is one negative that stands out. One postdoctoral researcher was a South Korean Assistant Professor, Un Jin Han, who worked diligently with me for over a year on innovative biofilm processes. His family included a wife and a young boy. When his wife was to deliver their second child, she flew back to Korea.

A few weeks after the birth, when she applied for Visas to return, the U. S. State Department refused to allow her to return. After much effort on my part, and with intervention by a local Congressman who was a personal friend, we were successful in having restrictions lifted so that she and her newborn could rejoin her husband in Ithaca.

When Un Jin completed his work with me in Ithaca, he prepared to return to Korea. He also wanted to duplicate some of the equipment I had, so he purchased equipment to mirror our research. He boarded the plane with his wife and family and headed to Korea with confidence that he would be able to continue his work with me in that far-away land. Later that day, I heard that the Russians had shot down a passenger liner, Flight 007, the flight carrying my post-doc, his wife and family. Several days later, I heard the first official confirmation that all passengers had been killed and that a picture of Un Jin was discovered on the Japanese seashore.

The most difficult task I had while at Cornell was to organize and conduct a memorial service for Un Jin Han and his family at our Sage Chapel. A few months later, to honor his work with me, I presented Un Jin's work at a Purdue University Conference.

VI. Commercial Activity

VI. A. Introduction

I was fortunate early in my career to provide solutions to several important environmental engineering and renewable energy problems, which led me to pursue high-tech commercialization in a number of ways. Early on, I thought that working through large companies (FMC Corp., Air Liquide, Air Products, DuPont) would be preferred, since they had the required resources, expertise, and experience. As noted in the section on *"Anaerobic Digestion Fundamentals"*, my first experience was a spectacular failure. One of the larger waste-management-equipment companies, FMC Corporation, required a "secrecy" (non-disclosure) agreement that prevented me from publishing important advances. Instead of using my experience to guide their in-house research, they proceeded to waste resources and time and eventually failed – for what turned out to be a minor oversight in their testing program.

Reasons that advancement in environmental fields occur very slowly, if at all, were a mystery, but were clarified after several experiences with existing companies. Negative experiences with large companies convinced me that even at a small scale, it should be possible to commercialize innovative concepts if resources were properly focused. My reasons for combining my academic career with commercial efforts was that by becoming personally involved with innovative technology commercialization, it would do one of two things:

- make a contribution to society while making significant amounts of money; or
- make me a better teacher.

Throughout my academic career, I pursued commercial efforts with that philosophy firmly in mind. Although the Cornell administration said they supported involvement of faculty in commercialization, in retrospect, I believe they had a negative view of faculty pursuing commercial efforts.

In hindsight, I must also emphasize that my appreciation and understanding of the tools required to be successful in business were naïve at best. I assumed that breakthrough science and technology held keys to successful commercialization. It turns out that they are minor requirements for many businesses, especially in the minds of the financial backers. Lots of other factors are required to commercialize new ideas, not the least of which are opportunity, money, and luck.

After spending significant personal resources over a three-decade period, without making any money, I am still baffled by the complexity of the commercialization process. I had technology, access to money, contacts, opportunity, and technology partners in a number of instances, and yet each time factors conspired to eliminate paths forward. I'll describe some roller-coaster rides of my commercial adventures and try to draw insight from these experiences.

If I had time and interest, I would write a book about my experiences straddling high-level academia and the commercial world. As with many things, however, real truth is stranger than fiction and, in retrospect, much of it seems incredible.

I have left out some details because they are too negative or personal to include.

VI. B. First Company – JI Associates, Inc., 1974

My first incorporated effort, JI Associates Inc., stood for "Jewell-Ireland Associates." Bill Ireland was my college roommate for two years and an electrical engineer. Our first big break was the US EPA's designation of the anaerobic expanded bed (a unique and totally new moving particle biofilm filter bed) as being a preferred and innovative wastewater treatment process.

As we continued to pursue opportunities, my friend and partner was living off an endowment that his father had left him after the liquidation of resort hotels on the coast of Maine. After a number of years of not making any progress, I asked Bill to dissolve JI Associates, as it made no sense for him to work full time and constantly lose money, while I continued to work only holidays, nights, vacations, and weekends. That was an extremely difficult decision.

I was having emotional difficulties accepting the level of Bill's sacrifices without seeing any potential success, while he continued to use his family's money. At the time Bill Ireland had three young children.

VI. B. 1. Energy-Producing Sewage Treatment Facilities – Beginning of Sewage Treatment Parks

A driving force for my commercial activity was my idea that anaerobic biofilm treatment of sewage could generate valuable energy and clean water. I considered that to be a major breakthrough in the field. Just imagine a wastewater treatment facility that actually generated excess energy instead of consuming huge quantities,[5] while at the same time completely eliminating sludge generation.

5. Publically owned wastewater treatment facilities in the U.S. consume billions of dollars worth of energy per

I imagined that successful commercialization would turn the field of waste management upside down.

VI. B. 2. US EPA Designated Jewell's Process – Free to Municipalities

By the late 1970s, my work was recognized as having significant potential. The US EPA designated my energy-generating wastewater treatment technology (based on the anaerobic expanded-bed treatment) as one of a few select innovative technologies that would qualify for 100 percent funding support for communities that chose to use it.

Two activities were set in motion that, if successful, would have provided strong support for commercializing this technology. First, the EPA's premier R&D center in Cincinnati started a project to provide "proof of concept" for my process. Secondly, my first company, JI Associates, was awarded a grant (not a contract, but a grant, which should have given us much more leeway and support to document and promote commercial potential) to test the system at the wastewater facility in Hanover, New Hampshire, a community that had expressed interest in adopting the technology because of the promise of 100 percent government funding.

JI Associates was a two-person operation running on money and resources to which Bill Ireland and I contributed. I was on sabbatical leave from Cornell and was associated with the U.S. Army Cold Regions Research and Engineering lab in Hanover. Awarding of the grant seemed like a dream come true; certainly it opened up an amazing opportunity to demonstrate the power of the technology and to provide the basis for commercialization.

When notified that the grant had been awarded, we naïvely started the project immediately without waiting for financial support to be put in place. As we were constructing pilot units in Hanover, and had begun to work out start-up scenarios, the EPA fund manager notified us that he wanted additional test information developed prior to funding. When I pointed out that what he was asking for was pilot data that the proposed EPA project was intended to develop, he insisted that data be generated prior to approving funds for the already-approved project.

This type of "Catch 22" occurred a number of times during my commercial career. In this case, the

year, and still are not very efficient, discharging quantities of nutrients that degrade essentially every water way, and generate huge quantities of sludge that must go to landfills, or is placed on agricultural land, much to the dismay of many neighbors.

chicken and egg problem was created when a federal grant manager got cold feet about proceeding with a new and powerful concept. This killed our first project, and it consumed precious personal seed funds and time, and caused a black mark against the technology.

VI. B. 3. US EPA Proof of Concept of Jewell Process Results

Meanwhile, back with the government "proof of concept" study, as the US EPA geared up to test my expanded bed, I had surprisingly little input on their planning. After they developed the program, they called and said they would like to have my comments on their design. Although it was irritating that they had developed the entire test program without my input, I agreed to review their material.

What I received was so different from my process that I told them that if they proceeded, it would likely fail. Essentially, they had specified the wrong size and type of media for moving bed reactors - totally different than mine. With hindsight, it is clear that they did not appreciate the significance of key and patented aspects. They had used what existed in textbooks as the basis of their design.

That was the last input I had with the EPA program to document my process. Several years later, I attended a conference where the project manager was presenting data on "my" process for the first time. Their pilot study was a total failure. I had expected it to fail, but not as badly as was reported in his paper. Unfortunately, the EPA had continued to identify the effort as a pilot test of my process. They should have seen promising directions even with their uncreative approach. But in reviewing information presented at the conference, I had a bad feeling that I knew why their results were so negative, and it had little to do with the process.

As I mentioned earlier, accounting for sulfur interactions was very important in applying anaerobic processes. It was ironic that many years prior to my work, I had come across outstanding anaerobic sewage treatment work that had been conducted at the US EPA Cincinnati R&D facility (the same facility that tested my process), which at the time was part of the US Public Health Service.

That effort was the first anaerobic domestic sewage treatment system in the world.[6] Why was this early work not successful? The process was highly successful, but researchers were working near

6. Of course, the septic tank put into practice in the early 1900s was the first anaerobic sewage system, but most applications were for single residences. The Public Health Service study used a modified up-flow septic tank that looked a great deal like what became known as the Up-flow Anaerobic Sludge Blanket process, the Dutch system widely adopted today.

public housing and sulfur odors made it objectionable. Aesthetics associated with mismanagement of sulfur doomed early development of energy-producing anaerobic technology.

Returning to the EPA report on my process at a major conference, during question and answer period I asked the author if they had used organic tests that were required to eliminate sulfide interferences. His answer, to my chagrin, was that he was not familiar with that analysis and that it might be necessary, since the tap water contained high sulfate concentrations (the same tap water that condemned the first anaerobic treatment by the U.S. Public Health Service pilot project). The lack of success by this "gate-keeper" was due to incorrect interpretation of results and was obviously another barrier to commercialization.

A patent on the anaerobic expanded bed was eventually issued. I had conducted significant R&D in the private sector on the expanded bed prior to being hired by Cornell. To avoid any suggestion of unethical use of the technology, I gave all the rights to my first patent to Cornell's Intellectual Property Division. The one caveat was that if the patent was issued, I would be granted exclusive rights to commercialize it. Some years later, without my knowledge, Cornell's intellectual property group granted a non-exclusive license to another New York company, making it impossible for me to commercialize the technology.

VI. C. Microgen Corporation

Various commercial opportunities continued to come my way. Also, I was sought after as a consultant in a number of fields. I did not enjoy general consulting, so in 1978, after dissolving JI Associates, I developed a Delaware company, "Microgen Corporation". From that point on, until the end of the 1990s, Microgen was a vehicle that I used to commercialize a number of technologies. I will describe some efforts in the following that appeared to have huge potential to solve society's problems, but eventually all fell by the wayside.

VI. C. 1. Energy-Independent Farms – A Reluctant Participant

After several business-plan developments and unsuccessful searches for Microgen funding, I became convinced that it was essential to demonstrate real-world capabilities before we would have business-world credibility to proceed with larger efforts.

Because we had used several million dollars of public money to develop low-cost energy production systems for small dairies (i.e., digesters), I was reluctant to enter this field. This changed because of two actions in 1980. First, was a personal attack by "friends" at a local agricultural business. While on sabbatical in 1980, a copy sent to Cornell administrators was forwarded to me. That letter suggested that it was unprofessional for me to continue to promote our unique farm-energy technologies that had been so successfully demonstrated over a seven-year period. They did not want me to continue publishing information suggesting that it was the most cost-effective technology and essentially a "breakthrough" in small farm systems. The letter stated that our development was not acceptable on farms in that it required a Cornell Ph.D. to operate the system. They recommended that Cornell should either fire me or ban me from this type of activity.

I was not involved in any commercial activity in this area when this criticism was leveled at me. I was deeply committed to helping small dairy farmers to obtain renewable energy, and I had spent considerable time acting in the tradition of Engineering Extension to transfer knowledge developed with Federal funding, even though this activity was not part of my job description. At the same time, the company writing the criticism was marketing a digester that was not cost-effective and had limited success. More than 15 years earlier, a similar system had failed at a poultry farm in England, just as the Queen was on her way to dedicate the digester.

VI. C. 2. Arizona Dairy Company Renewable-Energy System – Biggest in the World – 1982

After turning down many opportunities to work with dairies to build digesters in the commercial world, I was contacted by the largest dairy in the world, "The Arizona Dairy Company". They had a vertically integrated dairy operation with a total of 15,000 dairy animals at one site, where 5,000 were milked three times per day [Fig. 54].[7]

When initially contacted, I told the owner, Mr. James Tappan, that I would not be able to assist him, as I did not do commercial work in this field. He kept after me for a year and finally said that he would pay a round-trip air fare for me to come and look over his operation. If, after looking at it, I decided not to assist him, that would be okay.

7. The huge Arizona Dairy had a total of 15,000 milk cows on one site; by comparison, the average size of dairies in New York at the time, which were run by one family, had fewer than 75 cows.

In January 1981, I flew to Phoenix and saw one of the most impressive agri-business operations I have ever seen. Every detail had been worked out and the Arizona Dairy Company was a most successful operation. Capitalized at over $60 million, it hardly qualified as a "farm." The animals were treated like queens and were as clean as any I had seen on a dairy. As the cows made their way, automatically, to the milking parlors three times each day, they went through a total animal warm-water shower! (I should note that Mr. Tappan originally ran a small dairy in a rural community only a few miles south of Cornell.)

Figure 54. Overview of the Arizona Dairy Company, one of the largest dairies in the world, with total vertical integration of 15,000 animals, 5,000 milked three times per day.

I agreed to work with Mr. Tappan's company to build what would be the largest biomass processing system in the world. The design feed rate was 300 tons of manure per day. Microgen agreed to do this project as a "turnkey" project,[8] "at cost" plus a very small profit. After the digestion technology was installed, we would have the responsibility to solve related pollution problems at the Arizona Dairy and develop by-product markets. I envisioned making some bold progress with their wastewaters from the milking parlor and cleaning operations, which produced half a million gallons of wastewater per day. We had hoped that the application of a plant-based water purification system we were developing would generate recyclable-quality water with other useful by-products. Recovery and marketing of the digested effluent would also be highly profitable for this dairy.

VI. C. 3. Pilot Study to Define Design Requirements for Arizona Dairy System

Because of the unique climate and adobe-clay soil on the site, I told the owner that before proceeding with a giant first-ever system, we would need to run a pilot system to document engineering design

8. Our agreement was to have total responsibility for design, startup, and operation of the Arizona Dairy digester system.

criteria. We needed to ensure that the desert-dried animal waste that would be fed into the system over the dryer six to eight months a year in the Phoenix, Arizona, area, and that the wetter waste produced during rainy weather, would be acceptable in our innovative design.

For six months, many barrels of manure were trucked from Phoenix, Arizona, to our pilot unit in Harford, New York. That pilot study gave us the required insight into pre-processing, wetting, and sand separation that would challenge our design, since our design at the Cornell University research dairy had been developed with relatively uniform manure with little bedding.

VI. C. 4. Successful Turnkey Project at Arizona Dairy Fails to Launch Microgen's Commercial Efforts

By this time in my commercial adventure, I was aware that successful demonstrations of commercial projects were an essential aspect of new high-tech companies. I was hopeful that this project would be large enough, and that it would become the key "kick-the-tires" technology, which would convince investors that Microgen had business and innovative technology commercialization capabilities that would warrant financial investments.

With private assistance from members of our R&D team, which built and ran the Cornell demonstration project, we successfully completed the Arizona Dairy pilot project. After completing this study, a highly innovative full-scale system[9] was designed and built. The system was constructed under our estimated budget and, at 12 months after the construction started, was well within our projected time frame [Figs. 55, 56, and 57].

Considering the innovative nature of our digestion technology, it was a resounding success, especially to be scaled up from a 50-cow system demonstrated at Cornell's research dairy, to Arizona Dairy's 15,000-animal system.

The total capital investment was less than $110 per cow.[10] This favorably compared to alternative technologies, such as one marketed by Agway, which had capital costs nearly ten times that of

9. My innovative plug-flow design consisted of four rectangular-shaped digesters in a row, each with a volume of 100,000 cubic feet. Biogas could operate a one megawatt combined power- and heat-generation system continuously – enough energy to support all the needs for a community of over 1,000 people, and much more than was consumed by the dairy itself. The system operated with a feed preparation area that was essential to control feed viscosity, but with no feed pumps, no mixing, and no waste transfer pumps – a simple design that was highly revolutionary.

10. As I write this material I noted a reference in the U. of Maine alumni news to a digester system constructed in Maine at a cost of over $7 million for 1800 cows, or a capital investment of nearly $4,000 per cow! Or nearly 40 times the capital investment of the Arizona system.

Microgen's system. After Microgen personnel started the system, operation and maintenance were taken over by Arizona Dairy personnel. One field hand operated our energy system.

Our system operated for 14 years and had a payback estimated by Mr. Tappan of less than two years. Early in its operation, a small tornado crossed over the digester, ripping the top off one of the four-digester cells. It was repaired in less than a week, and the system was back to full operation at minimal costs. This ease of repair was one of the greatest benefits of our design.

Expectations that the Arizona Dairy project would be the wedge that enabled Microgen to attract more venture capital were not realized. Microgen did not aggressively pursue farm-scale energy technology application. "Sexier" technologies, such as biofilm applications, remained our focus.

Several other commercial companies chose to promote our farm energy design. But it is disappointing to note that, at the time of writing these reflections, 30 years after outstanding success at Arizona Dairy, efforts to make farms more energy-independent is not a national policy and has had limited applications. Today, there are fewer than 500 digesters on farms in all of North America, compared to over 7,000 systems that exist on farms in Germany.

Although I did not want to continue working in this field for a number of reasons, I did expect construction and operation of such a successful scale-up to have a significant impact on commercialization. There were several companies that did take up our design and are still in business. However, considering the potential of the technology, and widespread problems in the northeast dairy industry, its limited impact is very disappointing.

Figure 55. Feed preparation tank at Arizona Dairy where solids were mixed to obtain an average of 22 percent dry matter and sand separation prior to feeding into the plug-flow digesters. This unusually high liquid feed dry matter was identified in a six-month pilot study prior to designing and building the Arizona Dairy system.

Figure 56. Arizona dairy digester cell, 100,000 ft^3 in volume just prior to installing a flexible liner cover, showing a small layer of foam developed as methane bubbles to the surface.

Figure 57. Overview of the four-stage plug-flow system designed, constructed, and operated by Microgen; it was the largest agricultural waste digester in the world at the time [1982]. From right to left, building houses the cogeneration unit designed for 1,000 kW capacity, open feed preparation tank, first of four plug-flow tanks connected in series with the first having a white insulating blanket over the gas collecting cover.

VI. D. Solid Waste Ventures

VI. D. 1. Complete Recycle Unsorted Municipal Solid Wastes with Substitute Natural Gas as a Major Product

In the early 1980s, solving the municipal solid waste problem became part of the national R&D effort to use anaerobic digestion – an application that had been on-going in Europe for many years.

There was significant potential to apply my technologies in this area. In one of our largest efforts, Microgen became a lead contractor to determine the feasibility of building a 1,000-ton per day facility for San Diego. There were several elements that made this contract unique:

- it would use unsorted municipal wastes;
- it would have a recycle goal of 100%, i.e., complete elimination of solid waste;
- the facility would be built on California prison property; and
- the operation of the system would be by prisoners through California's very successful Prison Industry Authority.

Microgen had the responsibility for defining a system that would convert all organics to energy and other useful by-products. The team included contractors who specialized in everything from air pollution to labor dispute negotiators. The use of prison property for the system would eliminate the ever-present problems of locating a new site for solid waste treatment.

Another interesting part of the contract was that it locked in all members of the team using Stone and Webster as the lead contractor to build the first 1,000-ton-per-day facility; and if successful, ten other 1,000-ton-per-day facilities would be constructed.

Our feasibility study showed that:

- 98 percent of unsorted residential solid waste could be recycled;
- over $40-per-ton of substitute natural gas could be produced; and
- large quantities of soil humus would be generated that could either be marketed as a soil amendment or burned in an incinerator for additional heat and electricity generation.

Because all metals and plastics were removed, this humus fraction was predicted to be fairly clean.

To confirm Microgen's design specifications, and since no facility was digesting solid waste in the U.S., I recommended via Microgen Corporation that a pilot system be built and operated by a third party to confirm our innovative design. Little did I know how this most appropriate recommendation would eliminate opportunities in this area.

A one-ton-per-day three-stage pilot system was constructed in Ithaca and operated to specifications prior to shipping to the third party. Construction and six-month operation of the pilot on actual solid waste was documented in an operator's manual for our innovative approach using "dry fermentation" or high-solids digestion. This unit was then put in the hands of a third party for confirmation of the design and operating specifications. That pilot was operated over a period of years and confirmed our design for the 1,000-ton-per-day facility [Figs. 58 and 59].

Figure 58. Municipal solid waste conversion prototype developed to confirm Jewell's design parameters for Microgen's San Diego project. The three-stage system processed the "heavy" wet portion of MSW in anaerobic composting, and a biodryer step enabled material separation and humus recovery.

Figure 59. Humus generated from actual MSW by Microgen's ORCA system for the San Diego project [ORCA = "Organic Refuse Conversion Apparatus"].

Using that large feasibility and design study, all steps were taken to make a San Diego system a reality. Over a period of two years, labor unions were consulted and they provided their support and approval, air pollution permits were initially scoped out, and public hearings were held to determine San Diego's public reaction. All seemed to be positive to begin issuing bonds for the first unit, which was set at a cost of around $150 million, including the large financial costs.

This amazing project fell apart in a couple of spectacular ways. First, others recognized an opportunity to run with this effort and eliminate our large and talented team. Instead of proceeding with the lead contractor, Stone and Webster, as our contract specified, relatively inexperienced contractors were chosen to take further steps. No further action was taken with this exciting commercial possibility.

VI. D. 2. One Hundred Percent MSW Recycle For Maine Community

Over the years that we were working on the California project, Microgen pursued another parallel, but much smaller, effort – one closer to the digester size that I had been running at Cornell's research farm. After looking for a demonstration site for a complete recycle solid waste system, we identified a community in western Maine (Norway/South Paris). We spent a number of years working with their town council and developed an ideal "take or pay" contract for a 65-ton-per-day facility, which was an energy-generating complete recycle system. Our goal was the same as the California system – to recycle as close to 100 percent of unsorted municipal waste as possible. Over a three-year period, and without financial input from the community, our project went through the design stage, regulatory hearings in Maine's capital, public hearings in Norway/Paris, initial fund raising, and preliminary time-frame implementation. Public hearings resulted in strong public support for the project.

As the project was nearing early implementation, and we were in the process of receiving state regulatory permits, our construction and operating application was unexpectedly denied. Upon investigation, our project appeared to be refused permits at the state level because of concerns regarding existing commitments of the town's MSW to another waste management facility.

Microgen's activities in energy production from municipal solid waste continued for a number of years with several different companies. These included direct negotiations with sanitary landfill owners, hauling companies, banks, and others. I began to realize that little technology was involved with most solid waste management systems.

It was during these discussions that a particularly sobering experience occurred. I had come to know a regional landfill owner and solid waste management company. Our technology and their activities appeared to be a perfect fit to enable them to expand. Over a period of time, we began to look at financial support required to move into commercialization. One day, the CEO called and said that they had a meeting with a large commercial bank in New York City and they wanted me to attend the meeting. I agreed and was preparing to accompany top staff of this company on a chartered plane out of Binghamton. However, after considering the status of our discussions, and my level of input the night before the flight, I told the owner that I was not comfortable with our official status and would not attend this meeting.

The next morning I was called and told that the chartered plane that John was on had crashed and burned while taking off! John had survived because he was seated next to a door that flew open when they crash-landed. Later he told me that while he was paralyzed from nearly being cut in half by the seat belt, with the help of a farmer, he was able to drag himself far enough away from the plane to avoid being burned. Tragically, however, he witnessed his friends, colleagues, pilot and co-pilot burn to death.

That event occurred near the end of my involvement with energy from solid waste.

VI. E. Detoxifying of Anaerobically Digested Sewage Sludge – The SBIR Gold Ring

The SBIR program (Small Business Innovative Research) is one of our country's best ideas to assist commercialization of innovative technology. A small percentage of the budget of every Federal agency must be set aside to support small businesses involved in innovative R&D and commercialization. There is great competition for these $50,000 six-month projects, but the biggest incentive is that after an SBIR project is awarded, the next step, referred to as Phase 2, is subject to much less competition and chances are high of receiving a grant for over $250,000. This level of initial funding is substantial and provides a strong boost to commercialization success.

Our first successful SBIR project targeted my patented sludge-detoxification process (both pasteurization – complete pathogen and virus destruction - and heavy metal removal and recovery from complex organics, such as sewage sludge). This process is the only one in the world capable of purifying sewage sludge.[11] We wanted to show that all existing sewage plants could be retrofitted with the technology at minimum cost and very low energy input.

Important aspects of this project were:

- it was the first of its kind;
- it was patented (held by Cornell University); and
- it fit perfectly into the SBIR program goals.

In searching for a partner for this project, we found that Binghamton's sewage facility generated sludge with toxic metal content that was unacceptable when applied to land as a fertilizer, and they

11. The process has two patents and it provides destruction of pathogens and removal of heavy metals (cadmium, zinc, mercury, etc.), so the final product has composition close to cow manure and would not cause further environmental damage if applied to land, which is EPA policy.

became the site for the project. Results were successful and supported earlier lab-scale work. We had accomplished what few accomplish with a Phase I SBIR (a full-scale demonstration), and we assumed we would be guaranteed Phase 2 funding, which would have almost certainly provided support for commercialization.

Our subsequent Phase 2 application was rejected by the US EPA. When I pursued reasons why we were rejected, the project manager declared, "There was nothing new about your approach to detoxifying sludge."

When I noted that no technology existed that could accomplish: 1) removal of heavy metals from complex organics; and 2) the pasteurization of sludge with no additional energy or chemicals, he declared that I was wrong, without providing any further information, or allowing any appeal. This government gatekeeper was uninformed about technology in this critical area. Once again significant expenditure of uncompensated resources resulted in nothing.

VI. F. Patented Biofilm Reactors, Superfund Sites, and Complete Recycle Aquaculture

VI. F. 1. Commercialization Options

Another option for commercialization was to locate reputable and ambitious firms practicing in the area and try to develop a partnership. I contacted one such firm in Maine, which was headed by a former classmate and a casual friend. They indicated that they would like to talk about our patented energy-generating sewage treatment concept and invited me to make a presentation. After several meetings, and finding common ground, we were approaching an agreement that would put my technology in their hands.

In what I had thought was a final meeting to prepare documents to move forward together, I was asked several questions about another much larger sewage treatment equipment company. After several comments, it became clear that the CFO of my friend's company had initiated discussions with this third entity without my knowledge or consent, and prior to consummating our agreement. The discussion focused on selling my process to them, once the Maine Company obtained ownership.

I was disappointed for a number of reasons, but primarily because it eliminated my vision of how commercialization of my technology could move forward with me working with this Maine

Company and Microgen. Just as important, it demonstrated the lack of good faith and secure discussions.

VI. F. 2. Aquaculture Breakthrough

One of my more exciting but unpleasant forays into the commercial world revolved around improvements in my high-rate biofilm reactor, the "expanded bed process". By the mid-'80s, I held an important patent on a bioreactor that specified biofilm attachment media that enabled over a one-hundred-fold improvement over other bioreactors - a major breakthrough in harnessing and managing difficult microorganisms.

Limitations to a scale-up of the process included managing extremely small and light particles in an up-flow stream, and obtaining uniform flow distribution. This applied to all up-flow moving particle beds that were growing in popularity.

One day, a bright idea occurred to me:

- Why not reverse this whole picture, i.e., reverse the up-flow direction with particles denser than water? and
- Why not use a floating media with down-flow?

Doing so would eliminate flow distribution problems and the loss of particles in overflow streams. This would also result in a non-clogging filter.

A number of off-the-shelf particles were tested, including Styrofoam beads, and the concept was quickly proven at lab-scale. This led to exciting commercial possibilities that had not existed with up-flow reactors.

None of this work was conducted with Cornell University resources, so Microgen owned this new topic and I began to consider patent applications. Eventually a major patent was issued to Microgen for this highly innovative biofilm process.

VI. F. 3. Commercial Opportunity at Superfund Site

One of our greatest opportunities involved working on a Superfund site for a large chemical company. Timing of this request coincidentally occurred at the time I began to think about gathering resources to scale up our new floating bed biofilm process. After signing secrecy agreements that enabled Microgen to control technologies, we started a large pilot program to put a mobile floating bed unit at the site in New Jersey. We developed a special detoxifying microbial biofilm in a floating bed pilot at our Cornell lab (which we rented from Cornell), and once it was operating, transferred it to New Jersey.

Development of this new floating bed in a large pilot unit caught the attention of several individuals. It was obvious that it would lead to major improvements in diverse water purification applications, including recycle aquaculture. The size of a water purification filter using my technology would substantially decrease the size of the system, and therefore its costs.

To condense this story, the pilot was a success at the Superfund site. Microgen was selected as a contractor in several other Superfund sites. But our contact and the company itself was eventually eliminated, so none of the toxic bioremediation projects resulted in significant paths forward for Microgen.

During the Superfund study, I ran a short study documenting the floating bed potential in recycle aquaculture. During these trials it became clear that minor modifications could control all water quality parameters, and eliminate most chemical additions required to maintain fish health. I published this information without providing specific design details on the floating bed, as I did not want to publicly disclose this information until patent applications were developed.

Without my knowledge, however, another investigator decided to build and run the filter in his full-scale lab system. The process became known as "the bead filter", since it used Styrofoam beads as commercial material that we had identified as a good biofilm carrier. Again, without my knowledge, detailed design information was published and specifications on the bead filter were presented at a major international conference.

VI. F. 4. Early Disclosure Forces Patenting of Futuristic Bioreactor

The worst aspect of this unknown publication was timing of public disclosure that set a deadline for patent pursuit. According to patent law, a patent application is still viable up to a year after public disclosure. If a patent is not pursued after a year, the technology is considered to be in the "public domain", and the inventor loses any market protection offered by patents.

Unfortunately, I found out about the public presentation of my bead filter nine months after disclosure took place, leaving me three months to prepare and submit a patent. I spent nearly all of one summer developing the patent. Because the concept was fundamental, it would apply to almost any biochemical reaction created by microbes. The eventual patent was the longest of any patent I know of – 75 pages long. After two years of interactions, it was granted to and owned by Microgen.

VI. F. 5. Fate of Outstanding Technology – Biofilm Bead Filter

The bead filter was and is used in numerous small-scale aquaculture systems and Microgen has no role in these commercial applications. A year or so later, I was in the Cornell mail room when I heard the voice of a former Cornell administrator. I overheard him say that he had become a major investor in a nearby aquaculture system that was using a proprietary water-pollution-control filter. Although I never saw it, I assumed that this system was my bead filter. A few months later, I was at a party where several local investors were in attendance. A friend and one of the subsequent investors in a local aquaculture project came to me and congratulated me on the successful development of key aquaculture water technology in which he had invested – not knowing that I was not involved.

VI. G. DuPont/Conagra [Unsuccessfully] Purchases Microgen Corporation

Microgen had joint ventures with some of the larger U.S. corporations, and none was bigger than my association with DuPont. Our detoxification of chlorinated ethenes and successful renewable energy work with energy crops got their attention. One of their engineers, Mr. William T. Flukinger (WTF), noticed that we were recommending use of their flexible rubber-like liners as construction material to commercialize cost-effective digestion technology. WTF began to work with me and became convinced that I/Microgen had some valuable technologies. Over the period of several years, we made joint proposals to a number of industries that had great potential, but for various reasons, did not go anywhere – mainly because they were "ahead of their time", according to others, including WTF.

My dream of Microgen as a successful stand-alone commercialization entity was that it would exist close to Cornell, I would maintain at least a part-time professorship, and we would establish a mutually beneficial relationship for faculty and students attacking some of the Earth's formidable pollution and renewable energy problems. I was idealistic enough to think that should we be successful (at this time I just knew that we would be), there would be a distinguished chair professorship established at Cornell donated by and named after Microgen.

VI. G. 1. An Offer Too Good To Be True – Wine Company Proposal

The following is an example of how one can have all the components of a successful business venture and still fail. Our approach to one of the larger wine producers in New York, which I pursued with the assistance of DuPont and WTF, is a good example. I assumed that we had put together an offer that was absolutely too good to refuse. The apple juice and wine industries appeared to be prime targets for us. Large fruit-juice-processing companies had significant solid and wastewater problems. Apple and grape pomace disposal often resulted in transfer of this waste back to the orchards and vineyards. This can be a particularly poor practice since co-mingled material containing any diseases or chemicals becomes distributed to areas from which it was not generated.

Large quantities of organics in both wastewaters and fruit solid waste could be used to generate clean energy. Because of natural fermentation reactions, solid waste from fruit could be stored for long periods, to delay or modify energy production. Although the material presented difficult digestion conditions, years of work by my team had defined conditions that could guarantee stable energy production from such materials.

We put together a proposal that eliminated grape pomace and provided for the complete treatment of all wastewater, which far exceeded government regulation requirements for a nearby wine company. Microgen would design, provide funding, construct, and operate the system at no cost to the wine company. Their part of the agreement was to purchase energy from our waste-processing facility at three quarters of the cost of retail prices. DuPont would guarantee Microgen's system in that, if at any time they were not satisfied with our facility, DuPont would pay to remove our system and replace it with any system they specified – at no cost to the wine company!

A DuPont engineer, WTF, and I made what we thought was an excellent presentation – one too good to refuse. After delivering the presentation to a room full of wine company executives, we fully expected they would say, "Where do we sign?" Instead, our presentation was greeted with minimal questions after which the president said, "Thanks very much. We will be in touch with you if we are interested." The DuPont engineer and I walked out of that meeting totally confused as to what we might be missing.

After several weeks passed without contact, I called the president and asked if they needed more information to reach a decision. He said that they decided not to proceed with us. What a disappointment! Some time later, I found out that they were selling the company – to Coca Cola. I still could not understand why they did not want to proceed even with this complication.

Several large apple-juice producers in New York generate up to 50,000 tons of apple pomace a year, and other food processors also generate substantial organic wastes. We made several proposals to a number of these companies only to be greeted with minimal interest or negative responses.

VI. G. 2. DuPont Engineer Provides Assistance, Sees Amazing Potential of Microgen

William T. Flukinger (WTF) came to know me over a period of several years, developing feasibility studies for various commercialization routes, traveling to several potential projects, and making presentations that "were too good to refuse". During that time, DuPont and ConAgra formed a subsidiary, developed for the sole purpose of providing rapid movement and decision-making that are difficult for $40-billion to $100-billion-per-year companies.

WTF had been trying to get higher management's attention to buy Microgen and set up the ideal that Jewell had envisioned. With the establishment of this joint subsidiary between DuPont and ConAgra, it was a relationship "made for the times", so to speak. An attractive agreement was developed that would build Microgen as a stand-alone company and enable it to function independently. The DuPont/ConAgra subsidiary would be the majority owner and they would provide five years of core funding at $250,000 per year to support lab development and overhead. Jewell would be paid $125,000 per year for five years to work half-time for Microgen. Simple, to the point, and it fit my image of what could be accomplished in the pollution control/renewable energy fields.

VI. G. 3. Contract Details Terminate Purchase Discussions

Details were worked out over a twelve-month period. Two vice-presidents and Mr. Flukinger flew to Ithaca to sign the agreement. The night before the meeting, I was told that one additional person would be at this meeting, a DuPont lawyer, based in Switzerland, who flew in at the last minute. As far as I know, this person had not been involved in any of the year-long DuPont/Microgen relationship or knew any background about Microgen. After some small talk, this newcomer announced that he had made several changes to the original preliminary agreement (I did not think it was "preliminary", and was not pleased to hear this term). The changes were:

- Microgen would work only on DuPont or ConAgra problems; and
- DuPont or ConAgra, not Microgen, would automatically own all intellectual property.

Of course, such a relationship destroyed the concept of creating a stand-alone company that could grow and have close ties with Cornell University and its students. My response was not pleasant and I walked out of the meeting. Shortly afterwards, Mr. Flukinger took early retirement from DuPont and began to work nearly full-time to assist Microgen projects; in retrospect, this was a decision that changed the course of his life, and not for the better. He became another person entangled in Microgen's failed commercial activities.

VI. H. Demonstrating Resource-Recovery or Sustainable Wastewater Treatment at Full Scale – Somerton, Arizona

Under the North American Free Trade Agreement of 1994 (NAFTA) between Canada, the U.S., and Mexico, communities and industries within a certain distance of the U.S. borders were required to adopt "sustainable" pollution-control technologies. A special bank (the Border Environmental Commission or BEC) was established to support implementation of innovative, "sustainable", and specially designated technologies. Microgen was contacted by a consulting firm in Arizona to see if we wanted to compete for a full-scale demonstration of our resource-recovery technology that purified wastewater to near-drinking-water quality, while generating energy and other valuable by-products. We agreed and, over a period of several years, we developed a working relationship with the BEC, the international group in charge of defining, funding, and building sustainable technologies.

VI. H. 1. Jewell's Energy and Plant-Producing Sewage Treatment Concept Recognized as First Sustainable Technology in International Trade Agreement

Our resource-recovery system was the first sewage treatment system to be designated as meeting all of BEC's sustainable definitions, thus making it eligible for special funding by BEC's bank. We became the "poster child" for this part of the regulations and were featured on their website for a number of years. Our efforts to deliver technology included developing a detailed design for a border community – Somerton, Arizona – and public hearings were conducted to obtain community support. All steps to implement the technology were completed and we were preparing resources to implement this highly innovative system. All of this activity was accomplished without external support.

VI. H. 2. US EPA Eliminates Great Demo Opportunity

After receiving full approval from the community, we were ready to build the world's first energy- and by-product recovery system, which I referred to as "Resource-Recovery Wastewater Treatment". As we were preparing final steps to do this demonstration, I received a phone call from a "friend" who was an intermediate-level administrator at the US EPA, in the Washington, D.C., office. He began the discussion by indicating that he was aware of our efforts at Somerton. He said, "Bill, you know that's a complicated situation and not the best site for demonstration of your system."

I replied that I was aware of the complications (rural and very poor community, lots of illegal immigrants, etc., and some water chemistry that would be challenging), but that we were prepared to deal with them. He warned that the EPA did not want this demo at this site. I told him that if we waited for the perfect site, I would be in a nursing home before it happened, and that I was going to do everything I could to make this project a reality.

The US EPA region in charge of issuing permits to support construction of municipal sewage treatment plants in this area, assigned a young engineer to this project who had no understanding of our technologies. This young woman eventually refused to issue the required permits, without explaining why we were not allowed to proceed, even though the BEC and BEC bank had agreed to support the project. That ended our efforts with that resource-recovery wastewater treatment plant, in spite of the consumption of large amounts of time, personal money, and energy. Imagine the emotional roller-coaster ride of this multi-year effort!

VI. I. "No Holds Barred" Business, Academic Integrity, and Technology Progress

Providing an overview of my commercial activities is challenging because of the wide range of efforts and encompassing effects that they had. As an example, I will relate how one technology, with the potential to change the Earth, progressed in positive and, mostly, negative ways.

In the early 1970s, we were asked by the Federal Department of Energy (at the time called the U.S. Energy Research and Development Agency – US ERDA, and eventually becoming the U.S. Department of Energy – US DOE) to develop a cost-effective energy system for small farms. I responded with a $3+ million, 15+ year-long federally supported R&D program that was highly successful. Going from small-lab-scale fundamental research to full-scale long-term demonstration, the system we developed was highly innovative and challenged nearly all aspects of conventional anaerobic digestion.[12]

Our full-scale demo included parallel operation of a conventional system, "The Cornell University System". This comparison ran for seven years – perhaps the longest side-by-side full-scale comparison of digestion technologies ever. Our system was much more efficient, and it cost one-tenth that of the conventional system.

Our project was documented in numerous reports and papers that were presented at local, national, and international meetings. Without going into many science and engineering details, one aspect stood out overall: after a catastrophic failure,[13] our designs showed that it could be repaired and back in full operation in a matter of days (recall that an event did happen at the Arizona Dairy). Failures with conventional systems would put the system down either for months, or permanently.

There is one major engineering fundamental included in our system that was not (or at least should not be) subject to discussion. There are two main types of bioreactors: completely mixed and plug-flow. Between those two extremes are many varieties, but those two are well documented in all engineering literature. When choosing reactor types, one must consider the impact of reaction kinetics, mixing, toxic effects, heating, etc. Plug-flow designs – *by definition* – are over 20 times more effective than completely mixed designs, especially when high-efficiencies of conversions are desired. That is, the size of a conventional completely mixed reactor must be 20 times the size of a plug-flow system in order to obtain the same high efficiencies of conversion. This is not my claim; supporting documentation is found in all engineering texts dealing with reactor design.

Plug-flow that has no mixing, by definition, had not been applied in municipal sewage digester applications for obvious reasons:

First, economics plays a very small role in municipal systems. Digesters were thought to require dry solids' concentrations of less than a few percent, i.e., a water content greater than 98% of the wet mass. Without mixing, sewage solids settle and result in a disaster for sludge digestion.

12. Most of the 10,000+ conventional digester systems were developed for sewage waste treatment systems without concern for economics.

13. To measure fire and explosive potential of our approach, we threw a flaming gasoline-soaked rag on top of our unit. Although it burned vigorously with flames shooting 40+ feet in the air, we knew it would not explode. Buildings within 15 feet were undamaged. The system was repaired and back to full energy production in 24 hours.

More importantly, there are impacts from the methane fermentation reactions. These reactions initially cause acid to accumulate, which can result in highly toxic conditions. Digester mixing and maintenance of low solids minimizes these toxic conditions.

Consequently, municipal digesters are very large, operate at low solids, and have extensive mixing – all completely mixed reactor characteristics that make the digesters economically unattractive.

Our first goal was to develop a "cost-effective" design for small farms. The next was to develop a simple system that required little operational oversight. Conventional digesters, i.e., completely mixed digesters, require large-volume tanks and large energy inputs for mixing and liquid transfer. We started from the simple approach of eliminating all components of a conventional design and conducted basic research to determine which parameters were needed.

We started with a plug-flow design with no mixing. Shallow tanks, basically a trench in the ground, enabled us to use soil berms as side support; incorporating flexible rubber-like liners eliminated the need for major steel and concrete structural components. One reporter was heard to say that our digester looked like a "beached whale".

Our simplistic approach was the first to force the examination of digester fundamentals, including construction materials. Results of our multi-year effort were that with cow manure, the unmixed plug-flow, soil-supported, flexible liner design evolved as the best design in terms of efficiency, energy input, maintenance, and economics.

Without going into the large body of information we developed, some of the reasons why our approach was successful related to the feed composition, i.e., cow manure. With minimum bedding, dairy cow manure is generated at between 11 and 15 percent dry matter, i.e., ten times the dry matter content of sewage sludge. In this form, the viscosity is such that solids-settling and -separation is not significant, so mixing is not necessary if these minimum digester feed solids are maintained. Additionally, dairy cow manure is fully inoculated with methane-generating bacteria and is highly buffered, which in turn resists acid accumulation and lowers the pH in the absence of mixing.

Even when solids' concentrations and substrate concentration do not act like dairy cow manure, our approach is still the best approach for cost-effective and efficient digestion, although some modifications to support optimum digestion may be necessary.

Our work showed that if digester gases were used to replace other fossil fuels, including transportation fuel, energy-independent food production was possible. When we published this information in the mid-1970s, I expected it would begin to influence waste and crop residue management on farms. Today, there are over 500 digesters on U.S. farms, an insignificant penetration of the farm market where millions of farms could use this technology. This contrasts with 7,000 digesters in Germany alone. So why was this technology essentially ignored?

I cannot fully explain why my R&D was not sufficient to support commercialization. Our innovative approach had fully proven itself, information was widely disseminated, and the technology was free to be used without patent and/or proprietary technology. Even as we were writing final reports and encouraging farmers to consider the technology, it met with surprising indifference – and over 30 years later, it is still receiving little notice.

VI. J. Resource-Recovery Waste Management on Dairy Farms

In the *"Energy and Agriculture* section", a description of resource-recovery waste management on dairies is provided. Dairies, in general, but especially those located in the northeastern U.S., have been struggling for many years with milk prices that are less than the cost of doing business. Our approach to pollution control, and energy and by-product recovery, holds significant potential for this industry. I have made numerous presentations to dairy farmers in order to define demonstration opportunities. Because of most small farmers' limited economic viability, a cooperative farmer has not been identified. Locating a potential demo partner will continue for the foreseeable future.

VII. Lessons Learned by an Ivy League Professor in a Commercial Setting

My extensive commercial experience with Microgen Corporation had everything that one would think would lead to successful commercialization: a world–known leader as CEO, patents, scale-up jobs to demonstrate first-ever technologies; top level contacts in academia, large number of contacts with consulting firms and industry; available seed funding from friends and family, government, industry, and the business world; and successful competition for government funding in key areas (e.g., SBIR).

What was the outcome of this extensive foray into high-tech commercialization? Lots of interesting experiences, more heartache and disappointments, loss of respect among educational peers, sacrifice of nearly all weekends, holidays, and vacation time; challenges to my marriage, lack of recognition in both worlds, limited publication of significant and time-consuming efforts, personal losses of friends and colleagues who became entangled in the effort, and loss of income.

VII. A. Commercialization Tarnishes Academic Character

What are guideposts that I would set out for young people in academia who decide to combine a commercial effort with academic teaching and research? I would emphasize that anyone who is successful in science and engineering has the potential to make a contribution to the commercial world and to establish a successful business. Whether an individual decides to take up this challenge depends on many factors – many of which an academician is ill-prepared to deal with.

The first decision one has to make is which commercial direction to pursue: via a university's internal intellectual-property development system, partnering with an established commercial entity, or breaking trail with a new venture. The latter is the most difficult, most challenging, and potentially most rewarding alternative. I worked with all three options, but spent most of my time with the latter.

Recognizing and defining the opportunity is the first barrier. After appropriate R&D and demonstrations at sufficient scale to define a business entity, the concrete form this opportunity usually takes is the development of a business plan. This is the first big trap packed full of all kinds of problems for academics. Economics developed for such plans must show large, if not gargantuan, returns on investment. If assumptions show this to be possible, then recognition and material returns to the academic business developer must also be eye-popping.

Two problems are created by such a plan development: First, high-level researchers/educators are expertly trained skeptics and plans are never sufficiently completed so that the outcome is fully expected and defined before it is tested. Business models require exactly the opposite of what would be considered good academic attitude. In business, one must do everything possible to make results come out as one predicts, or even better. Failure means the death of the project. But in research, introducing any bias and manipulating a project to achieve expected and/or predicted results is considered cheating or fraudulent. However, a "failed" research project is, in many cases, a success, because it defines what does not work and it often opens up new and better questions and directions.

The second issue relates to economics and "over-the-top" expectations. If the return-on-investment is sufficient to satisfy venture capital investors, then the return to the inventor/plan-developer must be enormous. This perspective leads one to have unrealistic expectations. This is especially true for academicians whose salaries are modest at best. In every case, with the four or five Microgen business plans I developed, modest assumptions (at least in my opinion) for market penetration – and profitability – resulted in huge returns, almost always so much that revised assumptions were made to lower returns from gigantic to huge. The main impact of the business plan on the developer is to cement in place great expectations. This is required to ensure that the people involved with making the venture happen will have the incentive and drive necessary to carry a project to expected fruition.

All of this is experienced by every business start-up. But academics are highly idealistic and not necessarily equipped with the emotional tools needed to deal with business success and failure. The steps required to build early support for a business can send one on an emotional roller coaster. With engineering and scientific R&D, a "failure" represents a learning experience and provides positive guidance for new directions. An unexpected new direction in R&D is often the best outcome that can occur, because it will eventually provide insight that has never occurred before and may lead to whole new areas of research.

On the other hand, failure to achieve goals and objectives of a business plan represent failures in the business world. Funding sources rarely tolerate unexpected new directions, time delays, or improvements in something that had already been set in stone. Improvements or changes in directions are possible, but not until some success has been achieved. This is a situation that I experienced repeatedly with business associates.

Nearly four decades ago, I had developed great insight into using oxygen-dependent processes and thought they held great potential. When I recognized their limitations through fundamental research, and suggested to my huge business partner that we reverse directions and develop an anaerobic process (one in which oxygen is toxic), they thought I was nuts – and promptly terminated our development agreement.

VII. B. Truth and Consequences

Engineers and scientists, especially academic ones, are essentially truth-seekers. In business today, this is a poison pill for many projects. We recognize that there is no such thing as a certain outcome. There are always statistical values assigned to results, both proven and expected. When a financial or business person asks the academic business person, "Can you guarantee the results shown in your projections for return on investment?" The answer should always be "No."

Other questions that I have been asked are:

- "Can you guarantee that your project will achieve the stated efficiencies, product, etc.?"
- "Can you say for certain that no competition is out there?"
- "Can you guarantee that the patent in progress will be granted?"

The correct answer to all of these questions is, "No, I cannot." I would try to qualify my answers by saying: "There is always a chance for failure. I don't think it is significant, but it may fail."

VII. C. Personal Commitments and Life Leverage

Many people turn to venture capital to start new businesses. If the business plan shows monstrous returns, chances are that venture capital will be available – under the right circumstances. It is at this time that lack of business, financial, and legal experience by an academician often leads to extreme disappointment.

Venture capitalists expect failure for many projects, but also a few must earn very large returns on successful start-ups. Large returns mean making hundreds to thousands of percent on initial investments. In order to accomplish these returns, key personnel must be wrapped into the project in such a way that they have no choice but to sacrifice everything for the company. It took me some time to learn lessons in this area, but the following experience emphasized commitments that business investors expected of me – expectations to which I would never agree under any monetary circumstance.

Cornell University and the State of New York enticed a venture capitalist to come to Ithaca to set up a firm to support new businesses based on Cornell's ideas. This person was given access to $60 million for this purpose. I made a pitch to this firm thinking that I had a perfect opportunity and fit for one of my ideas.

After making the presentation, the venture capitalist asked me a few questions:

- "Had I taken out a first and/or second mortgage on my house to support the business?"
- "Was I willing to quit my tenured position at Cornell University to work full time for the start-up?"
- "Was my wife willing to give up her design business to act as secretary/treasurer to the business?"

Of course, my answer to all these questions was "No." He then said, "Bill, we want you lock, stock, and balls; and if we don't get that, you don't get our money!"

Tenured academicians are fully dedicated professionals. Unlike the leverage created by many business models, they are more often guided by idealistic leverages. My leverage for my job was always joyful and never felt like a negative force. I enjoyed my students and my teaching. When I gave a "good" lecture, it made my day, and a really good lecture made my week. I was always moved to tears at Cornell University's always-exuberant graduation, because my students were literally my children and I was saying goodbye to them as they left to enter the "real world".

What I enjoyed most was the creation of new knowledge via wet research projects. I always looked for key barriers to environmental or renewable energy problems, and that is where I spent my time. My greatest pleasure was when one of my research teams found key missing information that enabled us to solve it or at least move its understanding forward.

I never thought of money as being a significant driving force in directing my career. Cornell University went through a number of budget constraints during my tenure, and as a result, I did not receive any pay raises for nearly a third of my 35 years at the University. Unfortunately, this attitude towards money is a poison pill when seeking business support. I made the mistake of saying that money was not a high priority for me in a number of early venture capital presentations. I was being honest and wanted them to know that the opportunity to solve a pressing environmental problem, in the real world, was more valuable to me than making a pile of money. It took a couple of times for me to notice that when I would say this to the money guys, they looked like they had just bitten into a lemon! So, early on, I refrained from saying that earning piles of money was not a big driving force, rather it was THE driving force.

VII. D. Patented, Proprietary, or Fictitious Technology

Academicians do not respond well to business models that tie up key technical or scientific capital in a high-tech business start-up, and/or envelope efforts with secrecy and shrouds. A key component of new high-tech businesses is to have protected new concepts that have many beneficial uses. The way to achieve this protection in the marketplace is to have the concept patented. At least it used to be. Most universities now have intellectual property management divisions that include patent development. Like most businesses, academicians have a contract that gives the institution all patents created while in the employ of the university. Disclosures of ideas and/or new advances that might be patentable are required.

This seems to be a straightforward situation, but times are changing, and academicians are neither suited nor equipped to work in the shadowy world of secrecy, patents, and proprietary information. Our incentives rest in getting information out to as wide an audience as possible, to impress our peers with our creativity, and not to hold it secure until it can be sold to the highest bidder. Our reputation and overall success depends on strangers knowing what we have done and potentially benefiting from our work.

As the holder of a half-dozen patents, my opinion is that they have become less valuable over the past few decades. This is partly because our patent office has become moribund by opening the floodgates to patenting life forms. In addition, costs of just holding today's patents are very high. Maintenance costs of patents prevent most small businesses from applying for and/or holding patents.

By definition, a patent divulges detailed information that enables a person knowledgeable in the field to replicate patent topics. Because of the way patents evolve, many business advances are held as secrets and/or proprietary information. Whenever I worked with a larger company, I was required to sign a secrecy agreement that would prevent me from using any information gained during my exposure to the company [outside my own patented area]. This, of course, meant that I could not publish any related information, which in turn violated my main academic goal of creation of new and valuable public information. I would also require them to sign Microgen's secrecy agreement, even though I thought it a bit of a joke, since my legal recourse was essentially zero compared to those of a large company.

There are ways to get around some of this secrecy, and I always tried to make a positive effort out of commercial connections. Once I had a major deal with one of our largest chemical companies to develop analyses that could measure and document plastic biodegradability. Biodegradable plastics were, and still are, a hot topic in a world that spends over $20 billion per year on plastics. We had developed comprehensive biodegradation protocol in my Cornell work by the time I signed the company's secrecy agreement. In order to make the test available, I used a small amount of money from another project to support a student, who used the protocol as his master's thesis topic. By obtaining various plastic materials publicly marketed as "biodegradable", we were able to make an important contribution to this area without violating our agreement, which was not to mention or publish information on the products under development for the chemical company.

That project helped me understand the collective knowledge and limits of working with a large group of commercial scientists and business persons. One day while at the chemical company's campus, at a luncheon with VIPs and twenty other researchers working on the topic of plastic biodegradability, one of the higher-up business people strayed into a discussion of the true meaning of biodegradability. He mentioned that if they had a perfect biodegradable plastic, one that disintegrated into tiny pieces, it would be good for farmers' soils. I laughed and said that I doubted that farmers would appreciate having plastic polymers in their soil, no matter what the particle size.

I thought the VIP was kidding, since they were also working on real plastic biodegradability with me, i.e., conversion of carbon and other elements that composed the polymers into basic elements (chloride, carbon dioxide, water, etc.). My laughter was short-lived, as I looked around at grim faces that said they believed that degradation of plastic film into smaller particles was biodegradation, no matter that the mass of plastic did not change – a completely fallacious understanding.

As noted, engineers and scientists are, for the most part, truthful and honest – essential components of someone entrusted with the lives of many young people, millions of dollars of public funds dedicated to solutions of common problems, usually in the future, and given the great honor of working with public laboratories full of intriguing equipment, chemicals, and materials. Lying, cheating, and misrepresenting information are a few verboten areas that we find disgusting and repugnant.

Unfortunately, pressures of the business world create conditions that result in over-statements, misrepresentation, and lying. It also creates time constraints that may require less-talented persons, under stress, to make decisions that may seem illogical, but are a result of invisible constraints. Several instances occurred with Microgen that seemed less than ethical and sometimes close to illegal. One example occurred after our successful scale-up of the farm energy system at the Arizona Dairy Company. An acquaintance who was involved in the business in California subsequently stated in his business brochure that his company had designed and built the Arizona system – even though he had no connection whatsoever with that project. That level of dishonesty can be devastating, as one trained in academia neither expects nor knows how to deal with it. This can happen in academia, but it often results in substantial penalties, if not outright job loss.

I came across two cases of plagiarism in my career. One that directly affected me was with the California solid-waste project. As noted, Microgen developed a large pilot system that was operated by a third-party to document the engineering basis of a $150 million San Diego project. A pilot was designed, constructed, and operated by Microgen personnel in Ithaca. During over a year of operation, we incorporated much proprietary and practical information and data from several different solid-waste processing tests in a document we referred to as *"Microgen's Pilot Operating Manual for ORCA."* [14] After transferring the pilot system to the third party in order to confirm our design, portions of the operating manual were lifted word-for-word and published.

Although this example of plagiarism was professionally and personally damaging, another aspect had a more negative real-world impact. When Microgen was seeking funding to pursue smaller

14. ORCA = "Organic Refuse Conversion Apparatus"

solid-waste digestion projects, we approached several funding sources. The most promising funding source undertook a comprehensive "due diligence" search to confirm that my claims regarding origination and ownership of the technology were valid. When they traveled to the third party that was testing our pilot unit, they met with the individual who plagiarized our pilot work. In that meeting, he claimed that they were the source of information and refused to acknowledge that we were the originators of the technology and all the information. This resulted in rejection of our funding request and raised questions about our integrity. Anyone knowledgeable in the field would have clearly seen that this was Professor Jewell's work. Financial people unfamiliar with the technology have no basis on which to make such judgments, and so substantial damage can be done by such claims, especially during the financial due diligence process.

VII. E. Science And Technology Value Versus Money

Another important disconnect between academia and the financial world is the mutual understanding or, I should say, misunderstanding of the value of scientific knowledge compared to the value of money in the commercialization process. When I started with commercial ventures, I was under the impression that scientific breakthroughs that I had developed would be key to successful commercialization. After more than 25 years of trying to complete complicated projects, and attempting to raise funds, I now see that science and engineering capabilities can be a relatively small part of progress towards a successful high-tech business. Financial sources almost always believe that they have the most important component in moving commercialization forward.

Implications of the value of science and money are emphasized when one reviews what happens to technical entrepreneurs as a venture moves forward. In my earlier business plans, I envisioned that initial funding sources would receive up to 49 percent ownership in my company in exchange for startup funding. Early on, I realized that funding requirements would eventually take a larger share of ownership, and it could include giving up management decisions. Subsequently, decisions often resulted in lowering venture ownership to less than ten percent of the company, and potentially eliminating participation in the venture.

VII. F. Guilt by Association

Once I was startled by a comment from the Associate Dean of Research in CALS, as we were walking across the campus. After brief greetings, he asked me: "What kind of gimmicks or gadgets are you working on now?" insinuating that my research was practical-oriented and not really "research", at least in a fundamental sense. I was so stunned by this remark that I failed to answer, even though I think he meant no insult by the question. I always felt that although my research was aimed at difficult problems, the directions and content were firmly based in fundamentals of engineering and science.

Perhaps the greatest challenge of an academician involved in commercial enterprises is that some peers perceive it as an abuse of faculty positions. With requirements such as an extensive annual disclosure document, CU has taken steps to ensure that conflicts of interest and abuse do not occur.

I always made extra efforts to avoid even the perception that I was abusing my position. To be sure that no one would see any conflict, I always discussed with my immediate superior, the department chairperson, what I intended to do with my outside consulting or commercial work. I included work I did in university documents, such as the disclosure and my annual evaluation. If any space was occupied or resources used (telephone, lab space, and/or materials, etc.) by Microgen, I estimated their value or asked my supervisor and reimbursed Cornell for the estimated amount. Under no circumstances did I use time during workdays to do consulting, outside of the allowed amount.

For a number of the larger contracts, I used students, full-time researchers, and faculty to assist me. Each time I employed a person who had any connection to Cornell University, they signed a consulting agreement that forbade their use of any Cornell University time or resources that wasn't expressly defined. The agreement also stated that they were responsible for all personal conflicts as a private consultant, and information generated during consultation belonged to Microgen, including any patentable advances.

We made no effort to hide Microgen-associated activities, and every effort was made to avoid perceptions that Cornell University was being used for inappropriate financial gains. None of my activities ever took place on the main campus. Our biggest project was the construction and operation of a municipal solid-waste pilot system as noted above. Once this project was completed, we invited all Cornell faculty, administrators, and students to a special banquet that was paid for by the commercial project. Over 50 people attended a sit-down dinner. After dinner, all the waste – table covers, dinner plates, biodegradable plastic utensils, etc. – was collected and fed into the pilot system, or ORCA (Organic Refuse Conversion Apparatus). That facility demonstrated the concept of complete recovery of solid waste in useful and valuable products – a burning flame represented the energy output, and recovery of all the digester effluent resulted in odor-free compost.

My benefits from Microgen ended up being very much over-shadowed by negative impacts. An average week for me devoted over 60 hours, many over 100 hours, to teaching and research associated with Cornell University. For over 25 years, all vacations, summers, and most holidays were devoted to the promotion of Microgen.

Total personal investment in Microgen included all contract and consulting income plus a commitment of more than $300,000 in personal cash. Not counting non-reimbursement of work time, my total investment in Microgen probably exceeded $500,000. My professional commitments also endangered aspects of my private life.

There is little doubt that real-world contact was worth a great deal in terms of making my teaching better and more interesting. This was the minimum that I hoped to accomplish during my commercial work, but I had little idea that the negatives would be so large. The following two examples illustrate the negative side of my experiences.

One day I was in a grocery store parking lot and was approached by the head of one of Cornell University's waste management institutes. After a few introductory comments, she said in a loud and aggressive tone of voice: "I think you should be ashamed of yourself!"

I was totally taken aback, and asked what she was talking about. She said, "For using your position for personal gain!"

I was so dumbfounded that I don't think I ever responded, but got in my car and drove off. Some personal gain!

The second confrontation was much more significant in causing a negative outcome of my commercial work. As time went on, and I continued to tackle large environmental and energy problems and successfully solve them at Cornell, I began to wonder when and where I might receive more obvious academic rewards. They certainly were not coming from my company. My teaching was going well and students gave me some of the highest grades possible for my courses. Every now and then I would get a note from the Dean's office saying a student had told them that I was the most important professor they had during their four years at the University!

I had attracted over $13 million in outside funding for my research program. At one time my group was composed of full-time employees equal in number to the rest of the department. As I contemplated my accomplishments, one day I wondered why my engineering department had never been awarded one of the many "distinguished chair" positions that honored prominent and successful faculty? I doubted that many recognized chaired professors had done more for the university than I had already done. After considerable discussion with my administrative managers, it became clear that my involvement with Microgen had eliminated any consideration for the top academic honors.

Everyone from the Department Chair to the President promoted involvement of faculty in commercial activities as being a desirable activity – at least verbally. Apparently, actually trying to do it had a different context.

Two other adverse factors affected my career and must have been somewhat influenced by my perceived commercial activities. First, even though I was an extremely successful fund-raiser and researcher, this did not protect me from receiving negative administrative decisions that affected my ability to continue with wet research. One of my most negative research experiences resulted in early termination of a multi-million-dollar toxic remediation R&D project. Our research on groundwater purification of the most common cancer-causing chemical had been so successful that we were asked to scale-up and do a pilot demonstration. That request was received as we had spent down the several million dollars of that year's funding in September. We were told, verbally by the funding agency, to continue and plan to expand the project into field trials, and new funding would soon be approved by the outside funding agency.

Two post-doctoral researchers and five other full-time researchers were involved at the time, but scale-up would have required hiring several more full-time engineers. In November, as we were spending several hundred thousand dollars of uncommitted money from our sponsor, we were told that they had decided to terminate our project and to fund another group (a private consulting firm). This meant several highly negative things: first, all full-time employees of the project were going to receive termination notices as Holiday gifts! Second, we had already overspent our budget by a quarter of a million dollars that had not been awarded. Although I was worried about the funding gap, my most serious concern was the negative impact on people's lives. My team had been together for three years on this project, and several individuals had been with me for five or six years. In addition, several of my full-time researchers were pursuing graduate degrees.

Another negative aspect of my work related to the highest honor that one could receive in engineering – appointment to the National Academy of Engineering. I was friends with and mentored by many members of the Academy. Among them were my Ph.D. advisor, the person who hired me at Cornell, the person I replaced at Cornell, and several consulting engineers with whom I had worked. Although information was collected by Cornell at one point, it was withdrawn before it was submitted. I can only wonder how my perceived involvement in the commercial world affected these decisions.

VII. G. Conclusions Regarding Commercial Activities

Much of my activity with innovative technology commercialization has been negative, and reviewing comments here raises obvious questions; mainly: Why did I do it? Would I do it over? And, would I recommend this type of activity to other academics?

As noted, my reasons were many fold for dedicating a large portion of my life and my family's life to trying to transfer some of my knowledge to the betterment of humankind via commercialization. I had expected that, should I be successful, there would be substantial financial rewards. Should my efforts fail in an economic sense, I would still have the knowledge to understand how academia affects the "real world", and that would make me a better professor.

There are many aspects of my commercial experiences that I do not understand, and many consequences that I did not expect. One thing is certain, however; when I look around at the fields of environmental engineering, ecological engineering, and renewable energy, I see my hand print on many aspects: terminology that I coined in several areas, new companies, and new important directions in pollution control, renewable energy, and ecological engineering.

In retrospect, the most important positive aspect of my commercial activities was neither money nor its impact on my academic career. Most important was blazing trails into unknown territory that nudged or forced others to face barriers or markets that would eventually benefit Mother Earth. While attending an international conference on renewable energy in Ontario, Canada, I came across a new company that was marketing a *"Dry Anaerobic Composting System"*. I engaged the young engineer tending the company's booth and asked her who had invented the process and where did the name come from? She did not know. I said, "It came from me."

She immediately dismissed this old guy and turned to another person asking for information about the process. At first I was taken aback, but then I realized that this company and several others would not exist if my students and I had not developed this new concept, and by campaigning in the commercial world, it provided incentives to others to try new ideas and markets.

Those technological advances would be the rewards for academicians to become involved with real-world commercialization.

VIII. Side Lights

Good research always raises more questions than it provides answers, a prerequisite to being on the cutting-edge of technology. Some interesting topics remain as I contemplate further R&D in my retirement.

VIII. A. Organic Foam Processes

Working with "high-shear field" aerators produced large amounts of foam and interactions in the foam, an unexpected and unwelcomed characteristic of this application. Examination of oxygen dynamics in foam on top of the aerobic, autoheated liquid composting indicated that much of the action was on-going in the foam. For this process, controlling the extremely fine bubble foams was more of a problem than an asset.

Years later, I began to work with a common environmental chemical known as PVA, or poly vinyl alcohol. It has many uses, including its application to new clothing as a "sizing chemical" to enhance appearance and texture. However, chemical plants that dispose of this organic compound have problems with low concentrations of this material partly because it creates large quantities of foam. In working with this material to define its biodegradability, laboratory reactors were also subject to the generation of very large quantities of foam.

These experiences came together for me when I realized that custom-sized bubbles could be created that would allow both liquids and solids to pass through, or be suspended, in foam systems. Such a system, with extremely small bubbles, would provide exceptionally large surface areas to enhance liquid and gaseous interactions. Voilá, a whole new concept of waste treatment processes was envisioned.

Such foam reactors might lead to unclog-able fine particle filters, or volatile organic stripping from air, or … many other possibilities.

What should I do with such a new and innovative concept? The Engineering Division of the National Science Foundation has a section with a mission to fund new ideas that represent high risk investments, but have a high return potential. I contacted the project leader of this division to try to find support for this new concept. The conversation went something like this:

Jewell: "I have this idea that could be the basis for a whole new approach to waste treatment and gaseous/liquid interactions. It has lots of potential, but is completely undefined at this time."

Government Fund Manager: "There is no such thing as a totally new concept. Everything is just recycled ideas."

Jewell: "But, I think this idea would have some very new, interesting, and powerful possibilities."

Government Fund Manager: "No way! Furthermore, all of our funds are allocated to pursuing research questions raised by senators and members of the House. We do not have the resources to chase after political questions and support people like you!"

Jewell: "But, your division has responsibility to fund high-risk, high-potential-return research."

Government Fund Manager: "Yes, and that is what we do at the urging of our politicians!"

And that is where Jewell's foam technology is today.

VIII. B. Biofilm Floating Beds and Counter-Current Flow Applications – Optimizing and Advancing Biofilm Reactors to Achieve Complete Liquid and Particulate Management

I could see shortcomings for up-flow expanded beds early in its development. Maintaining equal flow distribution and uniform bed expansion on any sizable unit is a difficult problem. In addition, managing particulates intermingled with biofilm attachment particles was challenging, especially as my specifications required particles as small and as light as possible.

One day, I realized that most of the shortcomings could be eliminated if the process was turned upside down, i.e., if the particles were lighter than water, they would float. This enabled a simple flow distribution scheme, such as overflow weirs, to achieve uniformly distributed flow. Particles would naturally find flow-paths through the floating particles, so gravity would take care of any suspended solids. This concept was reduced to practice and was the aquaculture unit tested at a 60-second hydraulic retention time. Microgen also used it in a pilot demo at a Ciba-Giegy Superfund site to treat groundwater heavily contaminated with chlorinated toxic compounds.

Further considerations of flow management resulted in discovering some very innovative directions for biofilm reactors. For example, using tall and narrow tanks as biological reactors cost more than shallow tanks. Changing this design variable influenced energy input and all other design variables. Recycling purified effluent in order to expand the floating bed downward, while the main flow went horizontally through the bed, resulted in a highly efficient reactor with shallow dimensions and low energy input.

Another variation led to suspended-solids-free effluent; the horizontal-flow floating reactor could use a recycled stream from the effluent end to the influent. A recycled flow in reverse to the inflow would, theoretically, completely eliminate suspended solids in the effluent, since the flow-rate towards the feed end exceeded the flow through the reactor. The above aspects were incorporated in a patent that was issued in 1998 (*Chemical Modifications using Biofilms*). At 75 pages, it was one of the largest biofilm patents ever issued.

VIII. C. Self-Purifying, Self-Pressurizing Digestion

Biogas derived from anaerobic digestion contains large amounts of carbon dioxide, some impurities (hydrogen sulfide, for example), and evolves from digesters as it exceeds a low solubility in water at ambient pressures. If methane could be used as a transportation fuel, it would be worth three to five times what it is worth in its raw state for stationary purposes, such as electricity generation. Automotive engines are easily converted to use methane, and millions of vehicles worldwide use clean-burning compressed natural gas as a transportation fuel, especially where air pollution is of concern.

Removing CO_2 and other impurities, and compressing biogas so that it could serve as a transportation fuel, requires substantial energy and technology. To achieve energy density equal to gasoline requires that methane be compressed to several thousand psig (pounds per square inch gauge). Several companies are marketing small systems to accomplish this on farms using off-the-shelf conventional equipment.

While contemplating possible conversion of biogas to a transportation fuel, I envisioned one of the simplest improvements. My idea was based on simple fundamental principles – water is an incompressible fluid, and differential solubility's of methane, CO_2, and H_2S/pH relationships can be manipulated to cause gas separations and/or purification. By combining these fundamentals I came up with a process that promised to generate compressed pure methane with little or no energy input.

Over the years, exploding reactors that occur when the gas lines become plugged emphasized the concept of self-pressurization. Since methanogens continue to produce gas no matter the pressure (accumulation of methane in deep lakes and oceans confirms this), and as long as there is no change in pressure around the microbial cells, they will be happy. This suggested that microbial reactions could be used to pressurize gas without any energy input, as long as the feed was introduced and the effluent removed without using any energy.

If a "space-lock" type of piston feed could inject organic matter in water into a pressurized reactor, while the other side of the piston received the digester effluent, this would result in the feeding and wasting of a digester without any energy input, while extreme pressurization was achieved automatically from gas generated by the microbes.

Since CO_2 is many times more soluble than methane (CH_4), a secondary reactor, where liquid is allowed to de-aerate at ambient pressure, then be re-injected back into a pressurized tank, should enable CH_4 to be purified in the off-gas. Transferring the liquid under pressure to and from the pressurized reactor, by manipulating the appropriate valves would enable this step to be accomplished without energy input.

This two-step process could be referred to as "self-pressurizing" and "self-purifying" digestion. A lab-scale unit of a small high-pressure gas container was constructed and tested with a feed composed of a mixture of diluted cow manure and pure cellulose. Proof of concept was obtained over a period of several weeks as the reactor self-pressurized to over 1,000 psig. This "proof of concept" work did not have any financial support, so further development was not possible. Also, by the end of the proof of concept work, I felt that this idea was either my greatest invention to date, or a big waste of time – and determining which would require significant engineering and economic analyses of alternative directions.

Several aspects of this impressive advance became obvious to me as I contemplated further work in this area. First, running a digester at several thousand psig would be difficult and dangerous, and would require significant R&D support to do it safely and successfully. I had no doubt that the fundamentals were sound and that adequate support would result in the successful commercial application.

My concern about further lab work centered on safety and danger of running pressurized reactors. One day, while feeding the first prototype, I turned the wrong valve on the piston feed unit. It opened the piston to the reactor pressure when it was around 1,000 psig. The inside of the piston shot across the lab impaling itself on the wall about forty feet away. If any of this effluent had hit me or anyone else, it would have resulted in a very significant injury.

Because of the potential of the technology, I disclosed the invention via Cornell's Proprietary and Intellectual Property agreement. After reviewing the concept for a year, Cornell's Intellectual Property Division decided to pursue a patent. Two years into my retirement, I was informed that Cornell was abandoning further prosecution of the patent application.

VIII. D. Resource-Recovery Future: Closing the Nitrogen Cycle in Food Production – Vermiculture, Lemna

As the world population increases, finding sources of high-quality protein will be one of the essential aspects of future food production. I examined two candidates for protein production—worms and duckweed (Lemna). Anaerobic digestion will have a significant role to play in any sustainable future, whether it is a primary energy source or whether it enables other renewable energy technologies to reach their potential, such as providing a non-fossil fuel to power liquid fuel production from biomass. As such, anaerobic digestion should be viewed not only as a source of renewable fuel, but also as a protein synthesizer and soil humus generator.

My work has only begun to scratch the surface of vermiculture applications. Early results show that worms can separate and concentrate microbial protein in digester effluents, while dewatering the material and providing a purified lignin-enhanced particle. Now, that is a good baseline from which to pursue further development.

My last lab research effort showed that low-quality hay (reed canary grass and switchgrass) has a significant value beyond biomass production as a renewable fuel and could be a source of other valuable by-products. A research paper from this effort was presented at an International renewable energy conference in Venice, Italy, in November 2012.

VIII. E. Role of Anaerobic Digestion in a Renewable Energy Future

Using low-quality biomass as a digester feed appears to have a significant but limited role in future renewable energy scenarios -- so limited that anaerobic digestion is almost never mentioned when discussing and funding future scenarios. This is unfortunate as the primary reason for this oversight is lack of knowledge by engineers and scientists more versed in other directions.

For many years, I have argued that anaerobic digestion is important for the following reasons:

- it is the only technology that is viable and fully commercial today;
- it is the only truly renewable fuel technology that when used, can conserve all required inputs and after many years of use, would result in improved soil and farming systems anywhere there is sunshine and sufficient water to grow plants; and
- it has a number of characteristics that make it more viable than simple technologies such as combustion, because it can generate protein, for example.

A calculation I made raised the potential of anaerobic digestion, on a worldwide scale, to a higher level than here in the U.S. If one calculates the quantity of biomass available as "non-food" organics, and assuming all the world receives a sustainable diet rich in plant matter, and assuming that all of the non-food organics are digested (and in many cases return the effluent to the soil to support soil improvement and increased food production), and convert this to the annual total energy produced, the quantity equals a significant fraction of the total worldwide fossil fuel consumption.

List of Figures

Note: To view a figure (in the digital version), click on its name below; use the "previous view" command to return to the List of Figures.

Figure 16. Comparison of data from lab-bench scale to pilot-scale to full-scale 100-cow dairy manure anaerobic digestion over a seven-year test program.

Figure 17. Burning plug-flow digester with flexible rubber-like liner showing result of "worst case" accident when a burning rag is thrown on top of the reactor.

Figure 18. Fire damage to Cornell University's plug-flow digester after intentional "accident" fire was extinguished. The top was replaced and within 24 hours biogas production was back to normal.

Figure 19. Several years of research were devoted to growing, harvesting, and estimating transport and storage problems for crops such as hybrid poplar and high-yield sorghum shown in this photo. New York sorghum is on the left, high-yield Texas sorghum is on the right with Prof. Jewell.

Figure 20. Commercial digester in Ontario, Canada, built at a beef feedlot. This digester is the same bioreactor design used in thousands of sewage sludge digesters, i.e., a completely mixed design; specifically, its the design that Jewell feels is not acceptable on small farms. This beef feedlot with several thousand head went bankrupt shortly after implementation of this multi-million dollar digester system.

Figure 21. Combined power and heat recovery engine tested for several years at Jewell's small dairy digester development project.

Figure 22. Illustration of components in a resource-recovery dairy-waste treatment system. Note that dairy manure and wastewaters are introduced and only useful and valuable by-products result.

Figure 23. Unmanaged land treatment system on the Genesse River near Rochester, New York, that caused great concern to regulatory authorities prior to Jewell's research at the site.

Figure 24. Uncontrolled "overloading" at the food-processing wastewater land treatment site showing ponding of wastewater that caused concern that it was contaminating groundwater

Figure 25. Example of unmangaged vegetation at New York food-processing wastewater land treatment site.

Figure 26. Average groundwater quality under the "poorly managed" food-processing wastewater land treatment site, emphasizing the huge capabilities of natural systems to purify wastewater under extreme loading conditions. Values from top to bottom are: total COD [chemical oxygen demand], BOD5 [five-day biochemical oxygen demand], TDS [total dissolved salts], chlorides [Cl-], NO_3-N [nitrate nitrogen], and NH_3-N [ammonia nitrogen]. All pollutants were removed by over 99%

Figure 27. Mass flow of nitrogen in the New York food-processing land treatment system, showing exceptional elimination of nitrogen in this relatively unmanaged wastewater control system.

Figure 28. Aerial photo of one of two sewage treatment facilities at Springfield, IL, with wastewater flow rates greater than 50 million gallons per day that used land treatment for the treatment and final disposal of all sewage sludge.

Figure 29. Sludge applied at Springfield, IL, land treatment sites.

Figure 30. Return flow groundwater from Springfield, IL, sludge treatment sites. Note the extremely high water quality that results from this "natural sludge treatment" option. Total costs of sewage sludge management using this natural system was less than one percent of alternative sludge management options.

Figure 31. Conceptual diagram of resource-recovery wastewater treatment that converts all wastes into useful products without any residual production.

Figure 32. Mr. James Basilico, USEPA's project manager for part of the resource-recovery wastewater treatment research project. Traditional government and industry support of highly innovative fundamental research is extremely difficult to obtain and requires brave and supportive project managers to withstand criticism of agency mission supporters.

Figure 33. Schematic of resource-recovery wastewater treatment system designed to test various loadings of different levels of sewage treatment at the Ithaca Wastewater Treatment Facility. Most test flow rates were in the 10,000-gallon per day rate. The test facility used unheated green house for the bulk of the test units, but one system was left uncovered to test freezing impact on NFT.

Figure 34. Photograph of Jewell's Resource-Recovery wastewater treatment pilot system, including unheated greenhouse and outside NFT treatment system, and a two-stage AFEB reactor treating raw, unsettled sewage.

Figure 35. Conceptual diagram of the solar-powered water filter created by NFT wastewater treatment.

Figure 36. Typical root mass accumulation that forms the solar-powered water filter in an NFT [nutrient film technique] system.

Figure 37. First stage NFT system using cattails [*Typha glauca*] to treat wastewater following anaerobic treatment of raw sewage, with the AFEB unit showing the size of cattails with Professor Jewell at the entrance to the channels.

Figure 38. One of the important characteristics of NFT plant treatment of wastewater was the exceptional effluent quality. Prof. Jewell holds influent raw sewage in his right hand and effluent in his left hand. Note that the beaker has numbers next to his hand emphasizing clarity of treated water.

Figure 39. Cut flower production in the NFT treatment of sewage represents one option for income generation. Other options that would generate significant revenue include botanochemical plant production.

Figure 40. Alternative plants were tested in the sewage treatment NFT, including this subsample of Elephant grass [Napier sp.] obtained from a wild sample in Florida. Plant biomass yields exceeded 100 dry mt/ha-yr with several grasses.

Figure 41. Outdoor NFT designed to treat 1,000 gallons per day of raw domestic sewage, in early growth stage. All plants in this test were wildlife food options. Note low nutrient stress caused smaller plants as well as a lighter green, indicating low nitrogen availability as the water quality increased from left to right.

Figure 42. Outdoor NFT designed to treat 1,000 gallons per day of raw domestic sewage. Influent is on the right. Effluent on the left approached drinking water quality. Note the lush green color at the influent where plant nutrients are in abundance, and the faded green color denoting nutrient deficiency at the effluent water quality.

Figure 43. Duckweed wastewater treatment channel designed to define growth characteristics of *Lemna minor* in sewage treatment.

Figure 44. Beaker containing subsample of duckweed [*Lemna minor*] emphasizing high water quality obtained with duckweed treatment of sewage, as with other macrophyte treatment with the NFT.

Figure 45. Bacterial indicator data from NFT sewage treatment. Although most natural plant purification systems are not capable of reducing bacteria to drinking water quality, the NFT system was able to achieve undetectable indicator organism concentrations at low hydraulic loading rates.

Figure 46. NFT treatment of sewage results in an extremely rich biological environment that supported many pests that waged biological war on the cattail monoculture. Relatively simple and inexpensive integrated pest management was used to control all insect problems. Note the dense aphid population on the cattail blade in relation to release of “aphid lions.”

Figure 47. Anaerobic composting lab-scale reactors showing high solids and no liquid.

Figure 48. Fundamental relationship between anaerobic digester dry matter content and reaction rates that formed the basis for operating a high solids or anaerobic composting reactor.

Figure 49. Full-scale test of anaerobic composting of straw

Figure 50. Handful of hybrid poplar wood chips used in test to determine the potential biodegradability in anaerobic composting.

Figure 51. Lab-scale tests of anaerobic digestion of hybrid poplar wood chips

Figure 52. Pilot-scale test of anaerobic digestion of hybrid poplar wood chips.

Figure 53. Graduate student, Larry Krupp, conducting biodegradable analysis of commercially available biodegradable plastics.

Figure 54. Overview of the Arizona Dairy Company, one of the largest dairies in the world, with total vertical integration of 15,000 animals, 5,000 milked three times per day.

Figure 55. Feed preparation tank at Arizona Dairy where solids were mixed to obtain an average of 22 percent dry matter and sand separation prior to feeding into the plug-flow digesters. This unusually high liquid feed dry matter was identified in a six-month pilot study prior to designing and building the Arizona Dairy system.

Figure 56. Arizona dairy digester cell, 100,000 ft^3 in volume just prior to installing a flexible liner cover showing a small layer of foam developed as methane bubbles to the surface

Figure 57. Overview of the four-stage plug-flow system designed, constructed, and operated by Microgen; it was the largest agricultural waste digester in the world at the time [1982]. From right to left, building houses the cogeneration unit designed for 1,000 kW capacity, open feed preparation tank, first of four plug-flow tanks connected in series with the first having a white insulating blanket over the gas collecting cover.

Figure 58. Municipal solid waste conversion prototype developed to confirm Jewell’s design parameters for Microgen’s San Diego project. The three-stage system processed the “heavy” wet portion of MSW in anaerobic composting, and a biodryer step enabled material separation and humus recovery.

Figure 59. Humus generated from actual MSW by Microgen’s ORCA system for the San Diego project [ORCA = “Organic Refuse Conversion Apparatus”].

Appendix:

Selected Articles, Brochures, Photographs & Certificates

Contents

A. Selected Articles

Jewell, W. J. "Natural gas from agricultural wastes". *Cornell: Engineering Quarterly*. 1977_v12_n1 p. 14-24

Jewell, William J. "Energy from cornstalks." *Cornell: Engineering Quarterly*. 1982_v17_n1 p. 27-34

Jewell, William J. "Removing toxic organics." *Cornell: Engineering Quarterly*. 1990_v25_n1 p. 25-29

Jewell, William J. "Sewage-Treatment Parks." *The World and I – A Chronicle of our Changing Era* – a *Washington Post* publication. February 1994. p. 189-195. [Not reproduced here]

Jewell, William J. "Land Application of Sludge Has Merits. *New York's Food and Life Sciences Quarterly*, issue on "Environmental Quality." v20_n3 p. 7-8 Vol.20. No.3. p.7-8.

—— "Bioremediation Could be Answer to Superfund Clean-up. [American Chemical Society brochure, "What's Happening in Chemistry", highlighting five most important research topics—featuring Jewell's work. p. 50-52.]

B. Brochures

First business card, 1977

JI Associates' first business brochure

C. Photographs & Certificates

Picture of Jewell's team of researchers around the mid-90s. Three became professors, and two became heads of commercial high tech toxic remediation companies

ASCE Life Member, January 1, 2006

Sigma Xi membership, Stanford University chapter, May 28, 1968

Certificate of Membership in the New England Water Pollution Control Federation, undated

ASCE Associate Membership 1963

JI Associates stock certificate

American Society for Engineering Education, October 1973

Jewell receiving the National Energy Award from the U.S. Department of Energy Secretary in 1988 in Washington, D.C.

Selected general interest citations are listed in the following table.

Publication	**Description**
New York Times – Science Times	Nov. 3, 1987; Section C [Science Times], p. 1. "Sewage Project Could Turn Waste Into Profit."
Ithaca Journal	Monday, May 30, 1988. "Professor's Experiment Turns Ithaca Sewage Into Sparkling Water."
The Christian Science Monitor	Tuesday April 28, 1987, p. 23. "How Plant Roots Transform Waste Into Clean Water."
Portland, Maine, *Progressive*	1987. "Plants Profit from Pollutants: Greenhouse Swamp Soaks Sustenance from City Sewage."
The Post Standard [Syracuse, NY]	Monday January 13, 1986. "Changing of the Garden: Plants' Roots Purify Wastewater."
The Globe and Mail [Canada]	Monday August 25, 1986. "Waste Coming Up Roses Is Goal of Plant-Based Treatment Project."
Nae Woe Economic Daily [China]	Article on resource recovery wastewater treatment.
Cornell Focus, College of Agriculture & Life Sciences [CALS]	Vol. 2, no. 2. New and Traditional Programs for the Quality of Our Environment: "Strategic Planning for the Future."
Cornell Alumni News	June 1992, p. 10. "Cornell's Inventors" - Faculty: "Dr. Jewell's neat Little Bacteria: Clean Ground Water May Be a Handful of Bacteria Away."
Cornell University *Discoveries*	March 1993. Results of Research in the Public Interest: "Bacteria Used to Clean Superfund Sites."
Cornell University *Discoveries*	February 1994, pp. 1, 4. Results of Research in the Public Interest: "New Process Can Create Sewage-Treatment 'Parks.' "
Popular Mechanics	July 1988, p. 18. "Plants Help Purify Sewage."
Popular Science	February 1994, p. 21. Environment: "Sewage Solution."
Reader's Digest	May 1988, p. 56. "Roses From Waste Water."
Biocycle	July 1998, p. 69-71. "Keeping Manure in a Closed Loop."
The Lab Sampler [A publication of Friend Laboratory, Inc.]	Fall 1988, vol. 1, issue 2. "Garbage Crisis: A Reflection of Crisis in Technology."
Included below	Donna Fennell with biofilm reactors she was running to document chlorinated ethane bioremediation. Dr. Fennell is now a professor at Rutgers University.
Included below	Picture of colleagues early in Professor Jewell's career: from left to right, Prof. R. C. Loehr, Patricia Dauplais, Research Technician, Michael F. Switzenbaum, Bill's first Ph.D. student, Bill, and Prof. D. C. Ludington.
Included below	Prof. W. J. Jewell's desk at Cornell was always neat and tidy.

A. Selected Articles

Jewell, W. J. “Natural gas from agricultural wastes”. *Cornell: Engineering Quarterly*. 1977_v12_n1 p. 14-24

NATURAL GAS FROM AGRICULTURAL WASTES

by William J. Jewell

This past cold winter, natural gas shortages which forced the closing of schools and industries throughout the North stimulated a growing interest in the idea of generating gas from waste organics such as manure. The possibility that such a valuable commodity as natural gas could be provided from a renewable source with the simultaneous solution of an existing waste-disposal problem has attracted much attention. At Cornell, the biological conversion of organics such as cow manure to methane and other byproducts has been under study since 1973, and ongoing work shows that it could become a reality in the near future.

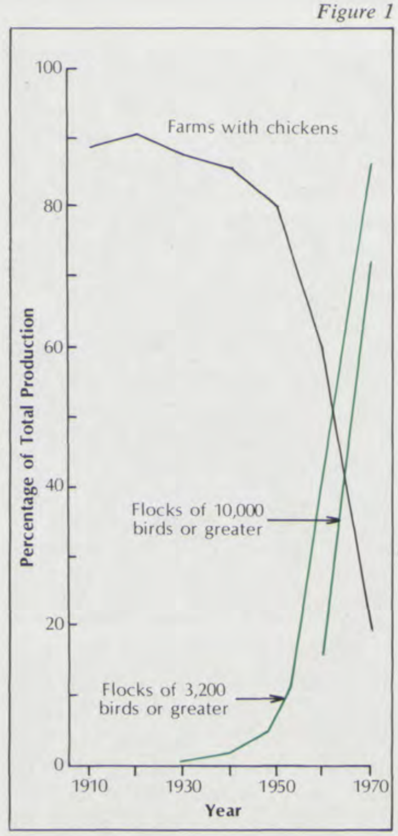
POLLUTION PROBLEMS IN FOOD PRODUCTION

The popular image of rural America is one of pastoral scenes far removed from urban pollution. Actually, however, there is a growing potential for pollution of the rural environment as food-production rates increase. United States agriculture has expanded at an unprecedented rate in the past two decades—the poultry industry (see Figure 1) is an example—and although large-scale agricultural methods are largely responsible for the beneficial increase in food-production capability, providing a great abundance of food at low costs, they have also intensified waste-management problems.

The quantity of agricultural residues is immense; the total waste produced by people as garbage and sewage is small in comparison (see Figure 2). A typical New York dairy farmer with about fifty cows spends up to 40 percent of his labor managing animal wastes that can be equivalent to the waste produced by five thousand people—and there are ten thousand dairies of this size or greater in the state. A poultry operation with one million birds can produce more waste than a human population of half a million.

The magnitude of agricultural residues emphasizes the need for effective management. When improperly managed, these residues may be washed off the land as a result of erosion. This runoff, unlike sewage, is difficult to observe and cannot be measured directly; agricultural residues containing runoff are part of the problem referred to as *nonpoint-source* pollution. Compari-

Figure 1



1

2

Animal-waste digesters can provide a source of fuel and simultaneously solve waste-disposal problems.

1. The only full-scale functioning animal-waste digester unit in the United States of which Professor Jewell is aware is this one located at a 350-head beef feedlot in Michigan.

2. Feedlots like this one in Colorado could make large-scale use of digesters to handle the huge amounts of animal wastes concentrated in relatively small areas.

3. A pilot-scale digester at Cornell's Animal Science Teaching and Research Center at Harford, New York, is large enough to handle the waste from three to five cows. This is a simplified anaerobic fermentor, called an unmixed horizontal displacement reactor, that is being developed for small farms. A feed tank located to the right of the reactor pumps the manure, which then flows by gravity under cover of a rubberized membrane. On the farm, a covered trench would be used. Laboratory personnel in the picture are Donald F. Sherman (left), research technician, and Robert J. Cummings, research support specialist.

4. Experimental work with a four-stage anaerobic digester model is carried out by Kenneth Fanfoni, research support specialist.

3

4

less costly means of methane generation can be developed. This is the main focus of the current ERDA-sponsored study at Cornell. The Cornell project is one of twenty or thirty in this general area of research that ERDA is sponsoring in university and corporate laboratories around the country. These projects range from small-scale and pilot-plant studies to large-scale test operations, and include thermophilic digestive processes, thermal processing methods, and biophotoloysis with algae. The wastes being worked on include animal manures, municipal garbage, and wood wastes, and the products sought include ethanol, nutrients, and oil, in addition to methane.

The national energy policy now under development will surely encompass at least three components: conservation, increased use of coal, and the development of renewable, clean energy sources. Anaerobic fermentation of agricultural wastes and other organics is a particularly attractive alternative for renewable, clean energy because it can supply a significant amount and simultaneously provide pollution control and allow valuable plant nutrients to be recycled. Manure and other agricultural wastes appear to be that rare phenomenon: an energy source with beneficial rather than detrimental side effects.

"...the crop residue from ten to twenty acres could provide all the heat required for a house in northern New York"

William J. Jewell, associate professor of agricultural engineering at Cornell, has major research interests—reflected in this article—in agricultural waste management, rural environmental engineering, land disposal of wastes, and biological and chemical mechanisms involved in pollution control. His activities in these areas also include industrial consultation, which has extended over a period of sixteen years, in a wide variety of pollution problems. His efforts to bring attention to the problems and possibilities of agricultural waste management include the organization of the first national conferences on rural environmental engineering (in 1973) and energy considerations in waste management (in 1974).

Jewell holds the B.S. degree in civil engineering from the University of Maine, the M.E. in sanitary engineering from Manhattan College, and the Ph.D. in environmental engineering from Stanford University. After completion of the doctorate in 1968, he spent sixteen months as a postdoctoral research fellow at the University of London and the Water Pollution Research Laboratory in Stevenage, England, under sponsorship of the U.S. Water Quality Administration. He joined the Cornell faculty in 1973, after teaching at the Universities of Texas and Vermont. His honors include a National Science Foundation Engineering Research Initiation Award.

He has published widely in professional journals, and currently serves as technical review editor for the Journal of Environmental Engineering *of the American Society of Civil Engineers, the* Journal of Environmental Science and Technology, *and the* Water Pollution Control Federation Journal. *He is active in a number of professional societies; at the present time he is serving as an elected member of the board of directors of the Association of Environmental Engineering Professors, as chairman of the American Water Works Association research committee on control of nitrates in the environment, and as chairman of the national research committee of the Water Pollution Control Federation.*

Figure 2

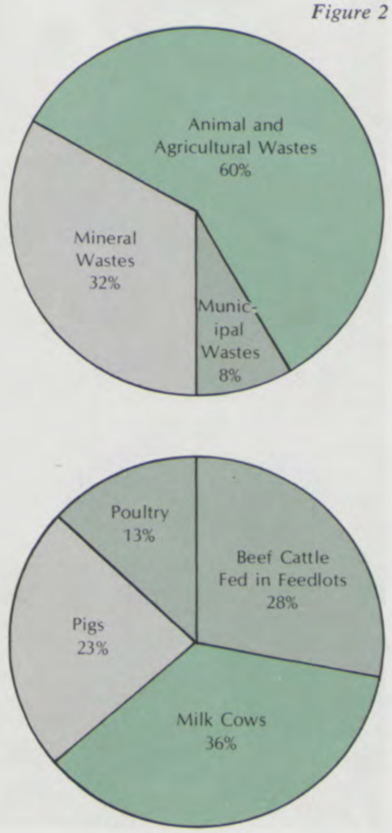


Figure 1. Chronological changes in the size of chicken-raising operations in the United States. The curves in color reflect how fast the industry is changing: for example, in 1962, 50 percent of all chicken-raising farms had flocks with more than 3,200 birds, but by 1968, 50 percent had flocks of more than 10,000 birds. The steady development of fewer and larger facilities has resulted in lower costs to consumers, but increasing waste-disposal problems.

Figure 2. Comparative amounts of solid wastes produced in the United States in 1969. The large percentage of animal and agricultural wastes (top circle) is subdivided into major groups (below).

son of this kind of pollution to point sources, such as domestic sewage, raises complex questions regarding cost-effective solutions for pollution control. A rule-of-thumb estimate is that in any watershed where the average population density is less than three people per acre, the nutrient pollution from runoff may exceed that from the raw sewage.

The issues involved in agricultural waste management include also the feasibility of converting wastes into usable products such as methane gas. At the present time, most agricultural residues are applied to the land in order to make beneficial use of their value as fertilizer. The possibility of converting the stored solar energy in farm wastes to methane *prior* to their land application is a promising area of investigation.

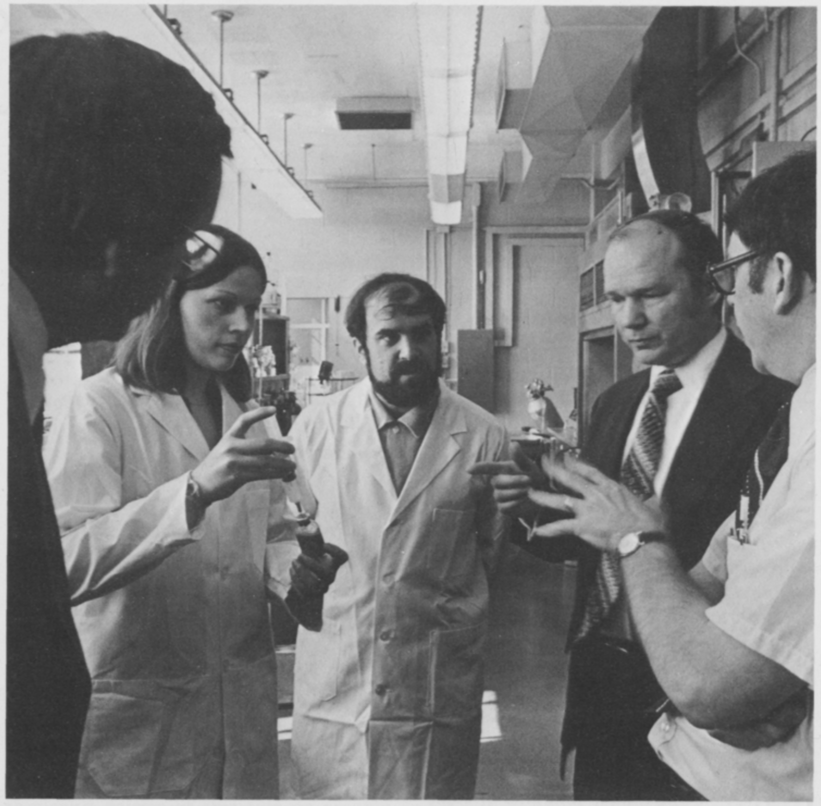
At Cornell, interest in the generation of energy is an aspect of an overall concern with agricultural waste management. A particularly active graduate program in agricultural waste management and rural environmental engineering has developed over the past twelve years. It has its roots in the Department of Agricultural Engineering, but it involves personnel in many divisions of the University, especially in the College of Engineering and the College of Agriculture and Life Sciences. Academic areas that interact with agricultural engineering in this program include agricultural economics, agronomy, animal science, poultry science, biological sciences, microbiology, chemical engineering, civil and environmental engineering, and rural sociology.

AGRICULTURAL RESIDUES FOR ENERGY: FACT OR FANTASY?

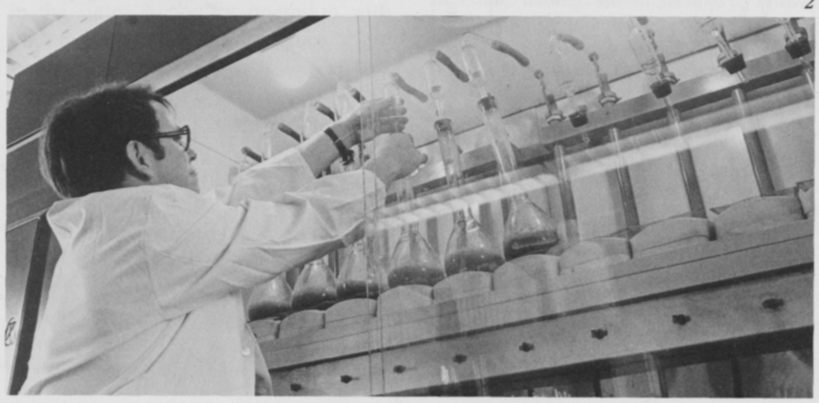
The vision of a manure pile being converted into a natural gas pump is an engaging one, but of course it bypasses the many engineering problems that must be confronted. Among practical questions are these: If the conversion were accomplished by anaerobic fermentation, would the resulting combination of carbon dioxide and methane be usable? Can significant quantities of methane be generated? Is the required technology available? Could it provide fuel to satisfy existing and future demands for food-production processes, and if so, would it be economically feasible? Would on-site use be the best utilization of farm-produced gas? Or would it be practical to make use of gas produced from agricultural wastes for nonagricultural needs?

These questions and others were examined by a multidisciplinary group at Cornell which studied the feasibility of

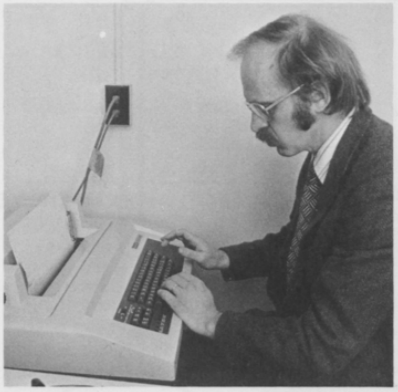
1



2



3



Members of the Department of Agricultural Engineering form the nucleus of the University's research program in agricultural waste management and rural environmental engineering.

1. The anaerobic digestion of manure is discussed by (left to right) Professor Raymond C. Loehr, director of the Environmental Studies Program; Patricia Dauplaise (holding a model anaerobic digester), research technician; Michael Switzenbaum, graduate student; Professor Jewell; and Professor David C. Luddington.

2. Professor Luddington supervises research in waste management.

3. Professor Douglas A. Haith works with the group as a systems analysis specialist.

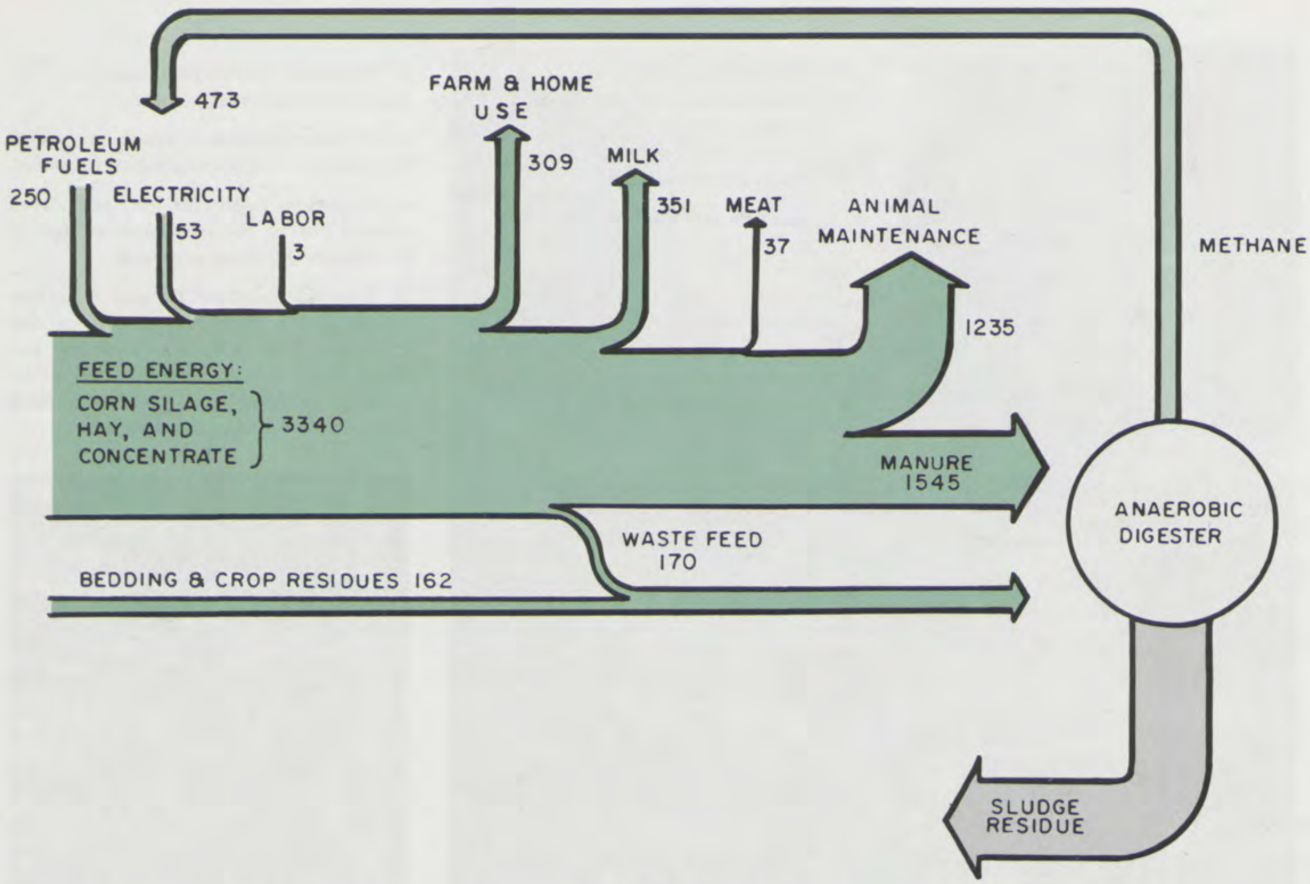
4. Professors Loehr (at left) and Jewell inspect one of the laboratory models of a high-rate methane generator.

5. Research associate Thomas D. Hayes works with a multi-purpose reactor that produces three effluents: methane gas; solid float material, potentially useful for bedding or feed; and liquid containing most of the nutrients for fertilizers.

4

5

17



producing energy from agricultural wastes.* Early in their study, the researchers estimated that on a national basis, the total amount of energy available from animal wastes and crop residues would constitute between 1 and 10 percent of the total energy usage. "Energy farming" of large land areas or the oceans could increase the amount of energy that could be generated. At a more practical level, the crop residue from ten to twenty acres could provide all the heat required for a home in northern New York, although even this small-scale technology is nearly totally undeveloped.

*The final report of the Cornell study group, probably the most comprehensive treatment of the subject now available, is *Bioconversion of Agricultural Wastes for Pollution Control and Energy Conservation* by W. J. Jewell, H. R. Davis, W. W. Gunkel, D. J. Lathwell, J. H. Martin, Jr., T. R. McCarty, G. R. Morris, D. R. Price, and D. W. Williams. It may be obtained from the Technical Information Service, U.S. Department of Commerce, Springfield, Virginia 22161.

Figure 3. Diagram of energy flow on a hypothetical 100-cow dairy farm equipped with an anaerobic digester for methane generation. The numbers represent millions of kilocalories.

The Cornell group considered various possible ways of using agricultural residues to generate energy. For example, processes based on high-temperature and high-pressure pyrolysis are available. The most promising method, however, appeared to be a microbial process of anaerobic fermen-

Table I
ENERGY USE IN MILK AND BEEF PRODUCTION*

Operation	Annual Energy Usage (kcal × 10^{-6}) Total	Per Animal
40-cow dairy	164	4.1
100-cow dairy	306	3.1
1,000-head beef feedlot	670	0.7

*In the U.S. in 1975. Includes energy used directly in the form of electricity, gasoline, diesel fuel, heating oil, and labor.

Below: These tanks composed the main methane generator constructed for a 100-cow dairy in Hornberg, West Germany, in 1952. Energy from this system would now cost more than twenty times the corresponding price of purchased energy.

tation to produce a mixture of carbon dioxide and methane gas, while leaving all the plant nutrients to be recycled in the stabilized humus material. This is the approach used in a project supported by the Energy Research and Development Administration (ERDA).

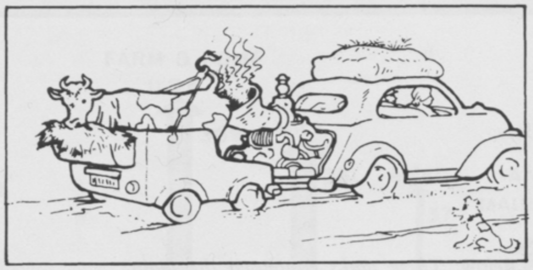
As part of the study, a comprehensive analysis was made of energy needs in the production of milk and beef (see Table I). A comparison (see Figure 3) of the fuel needs and the energy potentially available from fermentation of the organic wastes showed that the required energy could be entirely supplied by the methane generated from the manure, bedding, and milking wastes. Other analyses have also shown that energy potentially available from methane generation on farms exceeds the existing usage. The concept of a relatively energy-independent food-producing facility emerges as a real possibility.

ENERGY FROM ORGANICS AS AN HISTORIC IDEA

The concept of generating natural gas from organics is not new. As early as 1936, work in Illinois had progressed through pilot experiments to an advanced understanding of the process of energy production from agricultural residues. It was reported* that a ton of cornstalks would furnish enough gas for four hundred people for one day, allowing twenty-five cubic feet per capita per day, and that with 30 percent of the land planted to corn, a circular area eight miles in radius would produce enough cornstalks to supply a city of eighty thousand inhabitants with gas. The residue would be suitable for paper-making, the report indicated. The cost of producing the gas was estimated to be about the same as the cost of natural gas at that time.

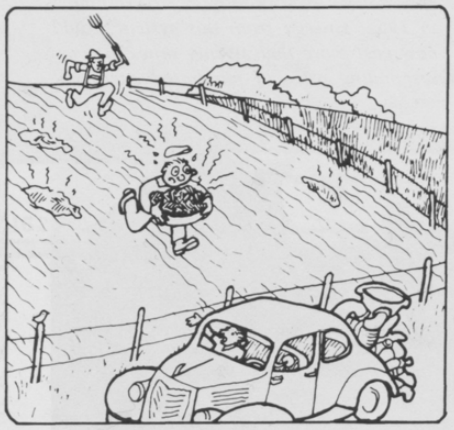
In the mid-1940s, several thousand farms in France were using simple methane generators. The popular press in Germany picked up the idea (see the examples of cartoons that appeared

*This classic report, *Anaerobic Fermentation* by A. M. Buswell and W. D. Hatfield, was published in 1936 as State Water Survey Bulletin 32 (Urbana, Illinois: University of Illinois).

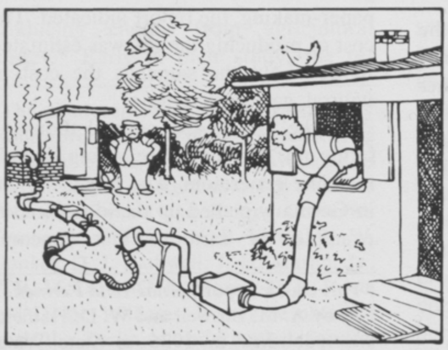


"Is it time yet, Bessie?"

These cartoons accompanied a newspaper story, published in Germany in 1944, which reported that a farmer from Limoges, France, had built an apparatus which generated gas from cow manure and which he used to run his machinery and for fuel in the kitchen and laundry. His system consisted of two 10-cubic-meter fermentation tanks which could hold a three-month supply of manure. The newspaper was published by the National Socialist German Workers Party.



"Run, Otto, here he comes!"



"There is enough for only one pancake—we have five people to feed!"

"Be happy, Lucie, by chance I was able to scrounge up a few miles of gas and we can drive to Potsdam tomorrow and visit Grandma."

around this time), and during the latter part of the decade, eighteen highly complex installations were built in that country. These systems provided gas for multiple purposes; a compressed form, for example, was used for tractor fuel. The problem with these systems was that the energy they produced was not economically competitive with the low-cost energy then on the market. Today, however, thousands of smaller and simpler units are reported to be either in use or under construction in India, Korea, China, and other developing countries.

The overall impression gained in reviewing the history of methane-generating schemes is that up to a few years ago, very little progress had been made in understanding and optimizing the technology as it applied to agricultural wastes.

FERMENTATION PROCESS DESIGN AND ECONOMICS

In order to evaluate both the technical and the economic feasibility of potential systems, the Cornell group modeled several for specific agricultural operations and estimated their capital and operating costs.

Three different types of cow-manure anaerobic fermentors—for conventional, batch-load, and plug-flow digestion—were built. The conventional system was essentially the same as the kind that has been used for many years in sewage sludge treatment; the batch-load unit was a practical system similar to one presently being promoted by a well-known German engineering consultant firm; and the plug-flow system was the simplest the group could develop. The design criteria for these three

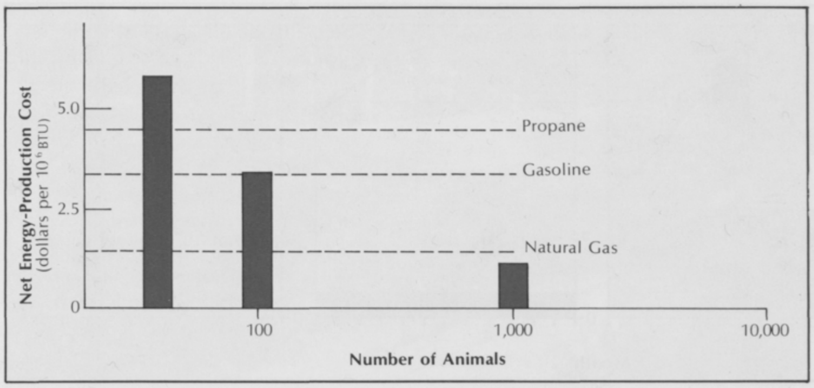


Figure 4. Estimated net cost of methane generated from agricultural wastes, as compared with commercially available fuels. The colored bars pertain to methane generated by the lowest-cost anaerobic fermentation system for 40-cow and 100-cow dairy farms and for a 1,000-head beef feedlot. The figures for propane, gasoline, and natural gas (at the federally controlled interstate levels) are for the year 1975.

types of fermentor are summarized in Table II.

These three systems were evaluated in long-term laboratory tests, including measurements of gas production. Costs for the least expensive system, the plug-flow design, are summarized in Table III for the three animal-production operations studied. The estimated costs of energy in the form of generated methane as compared with the costs of alternative, commercially available forms of energy are shown in Figure 4.

Although the data presented in the figure are encouraging, there are several remaining problems. For example, these costs do not include gas storage or cleaning or conversion of the gas to other usable forms of energy. If only half of the energy can be easily used at the agricultural facility, what happens to the remaining portion? The cost of conventional gas-storage equipment appears to be too high to be feasible on a small scale, and therefore the current prospect is that any gas that cannot be readily used must be wasted.

The possibility of selling excess gas to a pipeline company was included,

Table II

DESIGN CRITERIA FOR THREE TYPES OF COW-MANURE ANAEROBIC FERMENTORS

	Digester Design		
	Conventional	**Batch Load**	**Plug Flow**
Hydraulic retention (days)	10	32.5	30
Temperature (°C)	32.5	20*	32.5
Influent solids (% by weight)	10	10	10
Solids reduction (% of dry weight)	32 (50)†	38 (55)†	30 (45)†
Gas production (liters/gm solids)	0.27 (0.42)†	0.32 (0.46)†	0.25 (0.38)†
Gas composition (CH_4/CO_2)	65/35	65/35	60/40

*Two digesters operating on ten-day feeding plus ten-day batching schedules.
†Numbers in parentheses refer to wastes from beef-feedlot operations.

Table III

ESTIMATED COSTS OF METHANE-GENERATING SYSTEMS

	Farming Operation		
	40-cow dairy	**100-cow dairy**	**1,000-head beef feedlot**
Total capital costs*	$10,000	$14,000	$27,000
Annual operating costs*	2,460	3,300	6,300

*Include costs for pretreatment units, fermentors, and gas-handling equipment; storage of treated residue and the cleaning or storage of gas are not included. All figures were calculated for the lowest-cost option, the plug-flow design.

Figure 5

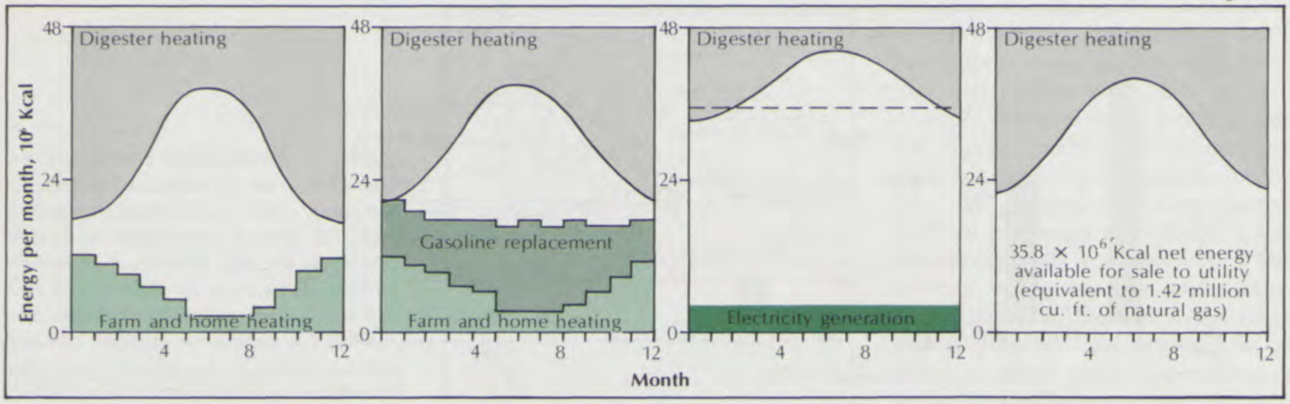


Figure 6

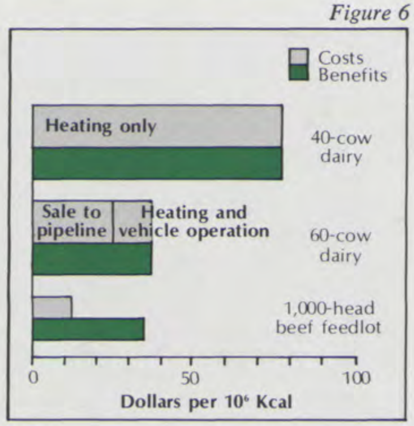


Figure 5. Monthly energy production versus energy demand for anaerobic fermentators. These examples of analyses made at Cornell pertain to a batch-load fermenter and gas-handling system for a 100-cow dairy, with the generated methane used for the indicated purposes. The open spaces represent excess quantities of methane; unless this excess were sold to a utility company (as in the diagram at far right), it is assumed to be unused.

Figure 6. Comparisons of costs and potential benefits of anaerobic fermentation systems. These examples are for conventional technology applied to three different animal food-production operations. The cost figures represent totals for energy generation and utilization. The benefits include labor reduction, odor control, and nutrient recovery, in addition to the energy obtained.

however, in an analysis made to determine the least-cost plan for biogas utilization. An example of the analysis data is shown in Figure 5, which pertains to a 100-cow dairy. The methane that could be generated would provide not only for home space heating, but also for water heating, milking-parlor space heating, clothes drying, and home cooking for one household. There would even be enough to serve as a replacement for gasoline used on the farm. During the summer months, at least, there would be a considerable surplus.

In an overall assessment of this technology, several factors other than energy production should be considered: potential benefits include also labor reduction, odor control, and nutrient recovery. Some sample comparisons of estimated benefits and costs are shown in Figure 6.

One significant conclusion drawn from the Cornell study is that even though few improvements have been made in agricultural residue fermentation technology over the past four decades, the method appears to be feasible for energy generation, pollution control, and nutrient conservation in many agricultural operations. Furthermore, it is reasonable to assume that improvements in fermentation technology can make the process even more attractive. The ongoing Cornell study is attempting to estimate the improvement that might be made with innovative applications and development of fundamental information.

Gas from agricultural residues represents a clean, renewable energy-production system that is the closest of any now proposed to being available at competitive costs. ERDA estimates that by the year 2020, about one quarter of our total energy needs could be derived from renewable sources, and that biomass could provide a significant fraction of this type of energy.

Perhaps the highest priority at this time is to determine whether better and

Jewell, William J. "Energy from cornstalks." *Cornell: Engineering Quarterly.* 1982_v17_n1 p. 27-34

ENERGY FROM CORNSTALKS

Local Crop Residues As a Substitute for Imported Oil

by William J. Jewell

While the United States continues its dangerous dependence on foreign oil, a substantial renewable source of energy in our own neighborhoods is being ignored.

Take the community around my hometown of Ithaca, New York, as an example. From our own resources we could be producing all the synthetic natural gas we need for home heating—the equivalent of half the total amount of fuel we use. We could reduce our consumption of foreign oil by three-quarters, decrease unemployment, improve the economic well-being of our farmers, and promote a closer sense of community. We could accomplish these things with a modest capital investment and without detriment to our environment. And what we could do, so could communities throughout the agricultural regions of the nation and the world.

The resource that could make all this possible is not an abundant gas well or a nuclear power plant or a solar-energy installation fifty years in the future. It is simply cornstalks, straw, and other agricultural residues gathered from the farms within a ten-mile radius of our city and converted to methane by hard-working bacteria. It is a resource we already have, usable by a technology that has already been demonstrated, and with few discernible drawbacks. Using crop residues for methane production doesn't reduce the food supply, deprive the soil of natural nutrients and mulch, pollute the atmosphere, create a hazard, make a noise, or impair the landscape. All it requires is a processing plant, some transportation and storage facilities, and a hookup to the municipal natural-gas supply system. The raw material could be trucked in by the farmers, who could then haul out nutrient-containing residue to spread on their fields and liquid fuel (alcohol produced in a separate fermentor) for their farm equipment. An additional alternative, now under study, is to use the biogas to fuel a cogenerator. This would provide not only electricity, but heat that would be wasted in the operation of a conventional generator.

The idea of using crop residues for producing biogas has been under development at Cornell since 1976. It grew out of a study of the anaerobic fermentation of animal manures that has resulted in the design of a successful on-farm reactor: about twenty units are now operating on farms and more than one hundred are probably under construction. Subsequently, the research effort was directed to crop residues, which have the potential for yielding much greater quantities of energy. Laboratory experiments progressed rapidly to pilot-scale operations, and by the fall of 1981, to initial testing in a full-sized reactor, suitable for use on a farm.

The research team in the Department of Agricultural Engineering estimates that two more years of intensive effort would have brought the process to a stage at which it would have been suitable for commercialization. Unfortunately, federal budget reductions have nearly eliminated solar energy R&D support, and the crop-residue-conversion effort has been discontinued, leaving the future of the technology uncertain.

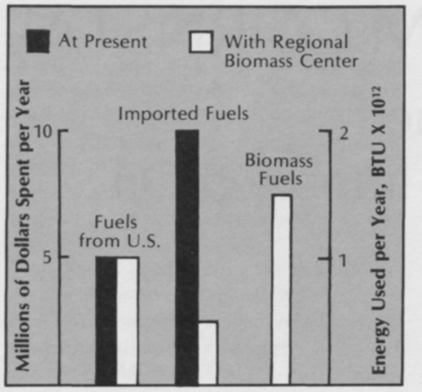
This article, therefore, is not only a

Figure 1. Energy sources and expenditures for a hypothetical United States community of ten thousand people living in a small city and on farms within a ten-mile radius. The total energy consumption is taken as $3X10^{12}$ BTU/year, valued at $15 million.

At present a third of the region's total fuel supply is produced in the United States and $5 million a year is returned to the nation's economy. Twice this amount of energy is imported in the form of oil and gas, mostly from the Middle East and Africa; this results in a flow of about $10 million a year to foreign countries.

With the establishment of a community facility for the production of $1.5X10^{12}$ BTU/year in the form of biogas, the need for imports would be substantially reduced, to $0.5X10^{12}$ BTU/year. The amount spent for United States-produced energy (including electricity) would be the same, but the annual flow of money to foreign countries would be reduced from $10 million to $2.5 million.

Figure 1



brief description of a promising energy technology, but a testimonial to the need for a national energy policy with balance and direction.

BIOMASS AS A RENEWABLE SOURCE OF ENERGY

One of the alternatives for tapping the energy of the sun is to extract the energy stored in biomass. In fact, biomass is considered one of the most promising of the solar energy sources, at least for the next few decades (see Figure 3). The realization of potential

Figure 2

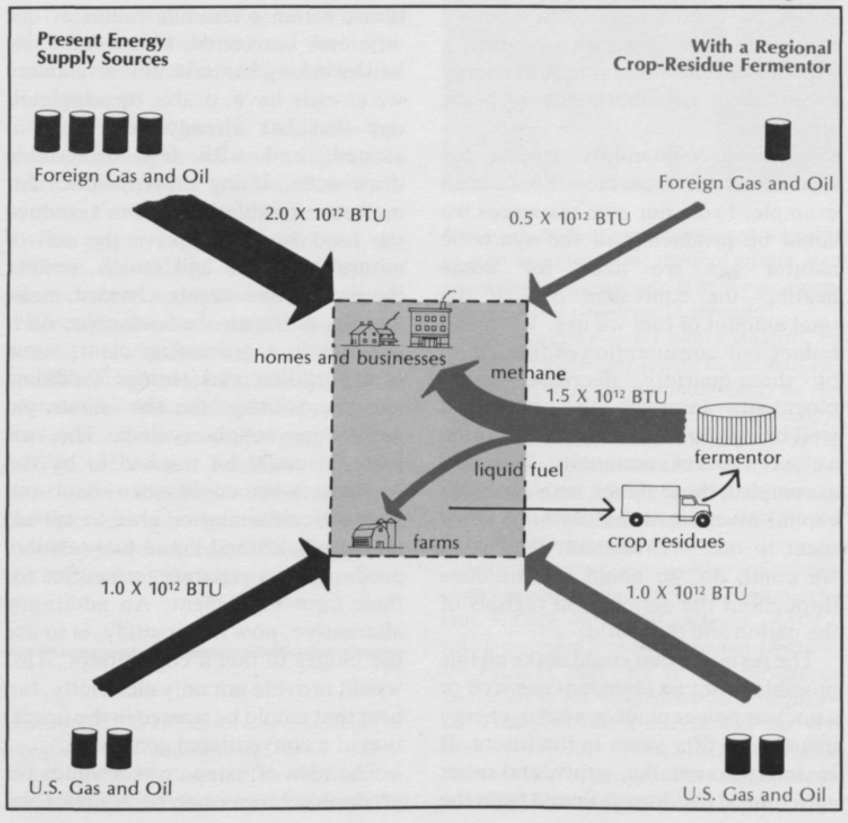


Figure 2. How the regional system of Figure 1 would work. The region's farms would provide biomass in the form of crop residues, yielding $1.5X10^{12}$ BTU/year. Some of this could be returned to the farmers in the form of liquid fuel produced by using a small fraction of the farmer's crop to make alcohol; this plan would provide additional incentive for participation in the program. Most of the output of the regional energy center would be used by the community in the form of biogas for heating, electricity generation, or other purposes.

depends, of course, on the development efforts. Funding for the biomass segment of solar-energy research has been low; in 1978 it amounted to 5.6 percent of the total for federally-supported solar energy research, and the prospects for the near future are even less auspicious.

The forms of biomass that are potentially feasible for energy production include aquatic and land plants grown for that purpose, and residues from forestry and agricultural operations (see Figure 4). Organic wastes, including garbage and sewage, can also be used. Biochemical and thermochemical processes can convert these materials to liquid fuels (alcohols and fuel oil), gaseous fuels (synthetic natural gas and hydrogen), electricity, or direct heat. Sometimes valuable by-products such as petrochemical substitutes can be obtained along the way.

Some of the biomass materials hold greater potential than others, and there are drawbacks and limitations to all the possible technologies. Wood, for example, is a good source of heat, but supplies are limited, especially if forests are to be preserved, and extensive use would be accompanied by problems of atmospheric degradation. Growing trees as a fuel crop would require land that might be used for food production. Using crops like sugar cane to produce alcohol, as is being done in some countries, depletes the food supply. Thermochemical conversion processes destroy plant nutrients and materials useful for soil conditioning. In addition, all the schemes are subject to economic constraints (which, however, may change over time). Among all the possibilities for

Figure 3

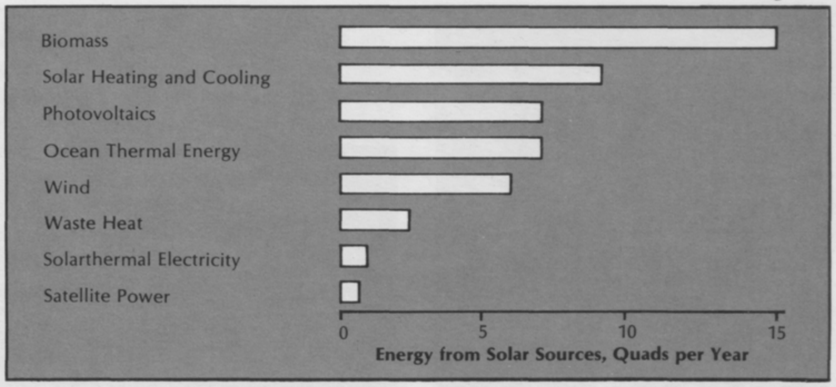


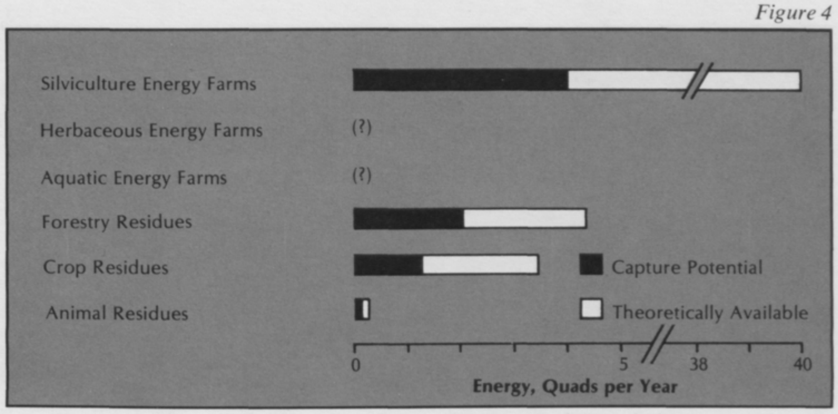
Figure 3. Estimates of energy that is potentially available from various solar sources by the year 2000. Waste heat *is from agricultural and industrial operations. A quad equals* 10^{15} *BTU.*

The figures are based on estimates from a dozen sources, largely government agencies. A more complete assessment would include considerations of additional quantitative and qualitative factors. These factors include the prospects for market penetration, the capability for rapid deployment, the potential for development that is not so rapid or so immediately competitive, environmental impact, the potential for conserving petroleum and natural gas, advantages afforded by on-site or decentralized operations, and effects on international relations.

Figure 4. Biomass residues potentially available for energy production. Capture potential *refers to the estimated amount that could be utilized feasibly. The larger potential of crop residues, as compared with animal manures, is apparent.*

Energy farms offer the largest potential, but are subject to contraints such as the allocation of land.

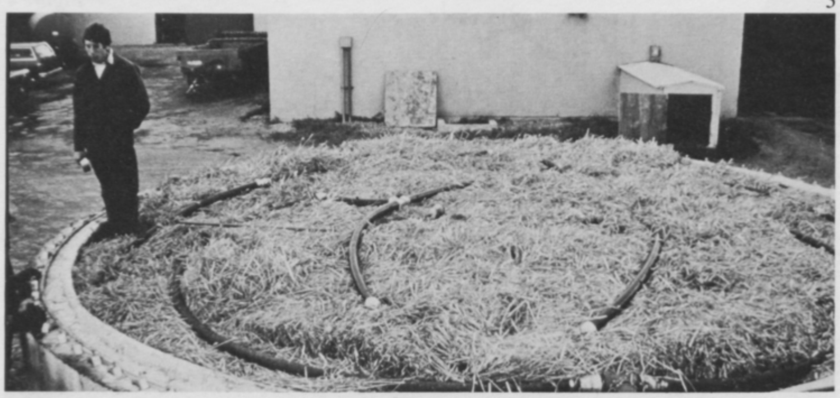
Figure 4



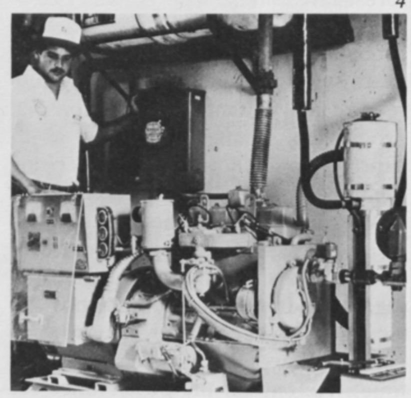
1

2

3



4



Left: Cornell's program to develop a dry fermentor for producing biogas from crop residues has proceeded through laboratory, pilot, and full-scale experiments.

1. The first pilot scale-up was attempted in 1978 with straw as the material. The reactor had a volume of about 5 cubic meters.

2. Here a prototype fermentor 110 cubic meters in volume is being loaded with wheat straw.

3. Fully loaded with straw, the prototype fermentor is ready for reaction. The pipes provide a backup system for moisture distribution and heating.

4. An efficient use of biogas is to fuel a cogenerator, which not only produces electricity, but conserves the "waste" heat. This 25-kW commercial cogenerator is being used at Cornell in studies that are now the chief line of research by Professor Jewell's group. The researcher is graduate student Roeby W. Ledford.

The efficiency of a cogenerator is about 70 percent. This may be compared with the 20 percent efficiency of a conventional generator run by an internal combustion engine. The 50 percent efficiency of the heat exchanger of the cogenerator—which is, of course, in addition to the efficiency of the electricity generation—approximates that of most hot-water boilers.

The electricity generated as part of a biogas-production system could be used by an industrial plant, for instance, or to operate a farm, or it could be sold to the local utility company. For example, if a farmer were paid 6 cents per kW (as required by current New York State law), he could finance the cost of the cogenerator in about two years. In addition, of course, he could make use of the extracted heat.

utilization of biomass, the conversion of agricultural residues to biogas appears to be particularly efficient, accessible, and inoffensive, especially if the nutrients and humus remaining after digestion are returned to the soil.

The production of fuels from biomass involves a wide range of technologies. Most of them have been known for a long time and many—such as methane generation from sewage sludge—have been commercially used in some form for decades. The primary task is to identify and develop those methods that are most suitable and economically competitive under particular circumstances of location and energy demand.

THE CORNELL PROGRAM FOR UTILIZING FARM WASTES

The biomass conversion method we have been working on at Cornell is fermentation by anaerobic bacteria, a process that yields a high-quality, clean gaseous fuel, a mixture of carbon dioxide and methane. The technology is commercially feasible; a large-scale facility in Oklahoma, for example, uses the residue from a 50,000-head beef feedlot. And the feasibility of small-scale operations is demonstrated by the successful operation of the Cornell-developed farmstead manure digesters. The total energy that could be derived from animal manures is relatively small, however; it has a potential value of perhaps $5 billion a year, as compared with annual imports at $60 billion. Much larger quantitites of biomass are available as crop residues (see Figure 4).

An immediately perceived advantage of crop residues is that they are available in a dry form and therefore can be transported easily. Not only farm-based facilities would be feasible, but units for residences or city buildings, and even large, centralized community plants. Unfortunately, however, fermentation processes work best with wet materials. Furthermore, crop residues are available only at harvest time, not continuously as manure is. Our first objective, therefore, was to develop an essentially dry, batchwise fermentation process that would work as well as the continuous-feed,

Right: Manure digesters, developed in the first phase of the Cornell program, are in operation or are being built on more than one hundred farms in the area.

"It is a resource we already have, usable by a technology that has already been demonstrated."

wet process that had proven so successful with animal manures.

ENCOURAGING THE BACTERIA IN DRY FERMENTORS

When we began the work with crop residues, little information about the requirements for dry anaerobic fermentation was available, even though the process has been used on a practical basis for many years by farmers, principally in Europe. We began with laboratory-scale experiments to determine the effects of moisture, additives, and temperature.

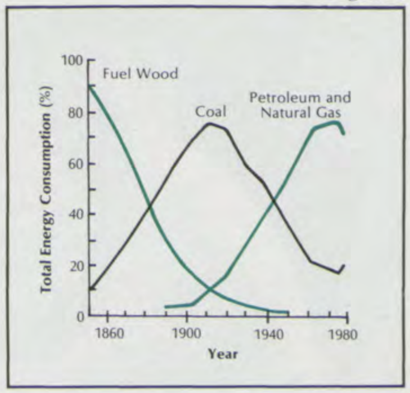
Moisture content was identified as the most limiting variable. It was found that for good fermentor performance (defined as one in which 90 percent of the solids that are biodegradable to volatile compounds can be converted in less than a year) the initial solids content must not be greater than 30 percent.

Another important factor is the kind and amount of bacteria-containing inoculum that is added to the reactor. Raw manure was found to be a poor source of inoculum, presumably because of the presence of large numbers of acid-forming bacteria that can overpower or reduce the action of the methane-forming strains. Dairy manure that had been digested was found to be effective, however, and was used successfully to start the reaction in subsequent experiments. Although the rate of gas generation increased with the quantity of inoculum added, our aim was to use the smallest possible amount in order to avoid the necessity of maintaining a liquid-slurry fermentor as part of the dry-fermentation facility. One way of minimizing the inoculum requirement was found to be a recycling, or "reseeding," of digested effluent. The penalty is a reduced overall rate of gas production, but this is not necessarily a drawback: gas produced over a year's time might be quite suitable for a digester that is loaded once or twice a year with crop residues.

Prevention of depressed pH caused by the formation of volatile acids, especially during start-up of the fermentor, was a problem in the early experiments. Sodium bicarbonate is effective as a buffer, but its use is undesirable because of the expense—which would amount to a significant fraction of the total operating cost—and because the presence of excess sodium would limit the usefulness of the digested residue. We found that the need for buffer can be reduced or eliminated by increasing either the water content or the amount of inoculum. After hundreds of fermentor tests, we have eliminated the need for expensive buffers and specialized bacterial inoculums. Moisture control combined with the addition of animal manure appears to be capable of successfully initiating the reaction.

Temperature was found to have the expected large influence on reaction rates. At 55°C extremely high reaction rates were observed, even with concentrations of inoculum lower than those used in the measurements at 35°C. The rates of gas production increased to peak values greater than seven volumes of biogas per volume of reactor per day (v/v-d). These results suggested that temperature regulation could be an effective way of speeding up or controlling the reaction rates. 32

Figure 5



Partly because of the promising laboratory results, the experiments were enlarged rapidly to pilot scale—with reactors up to five cubic meters in capacity—and last year to a full-sized, 110-cubic-meter reactor. Three readily available and representative materials have been tested: corn stover (the stalks and leaves), grass, and wheat straw. In the large reactor, wheat straw was used in the form in which it is available from the farm: bales of straw were simply packed in layers. The only additive was digested cow manure, in an amount sufficient to achieve a moisture level of about 75 percent of the total weight. Results have been very encouraging, with gas-production rates peaking at 0.75 v/v-d and still continuing at a significant rate after six months. During cold winter months, only about 5 percent of the output energy was required to maintain the process. Since the reactor does not require daily attention, the operation has focused on gas use.

It is difficult to compare the performance of a long-term batch dry fermentor with a continuously operated

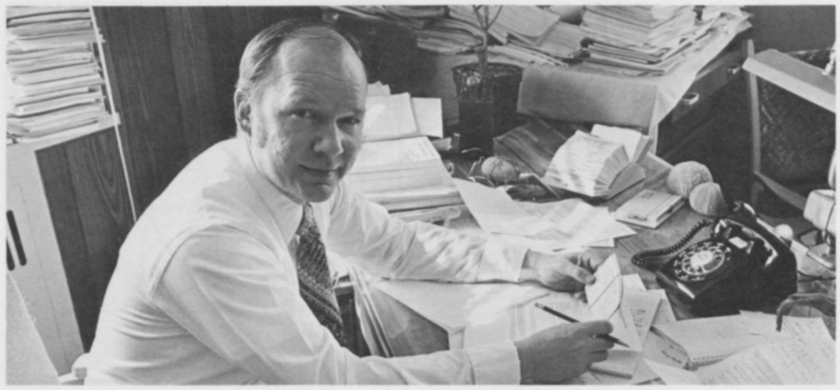
Figure 5. Fuel sources and major energy transitions in the United States. Wood was the first dominant fuel, then coal, and now petroleum and natural gas. The first two transitions were stimulated by technological advances that led to abundant, low-cost, clean, and more easily handled fuels. The present transition differs in that it is caused primarily by a decreasing supply. Another difference is that the time period for transition must be shorter: the first two transitions took place over periods longer than fifty years, but the present pattern of energy use must be changed in about half that time if serious shortages are to be avoided.

slurry system; still, our results suggest that a dry-fermentation reactor two or three times the size of a slurry reactor could produce the same total amount of gas over a year's time. Such a schedule would fit well with harvesting times for many crop residues, but if higher reaction rates were desired, they could be achieved at higher, controlled temperatures. The amount of labor and attention required would be considerably less for the dry reactor.

THE POSSIBILITIES AND THE PROSPECTS

Much work remains to be done. We know the dry-fermentation techniques work, but we don't know in detail what occurs at the molecular level; further research is needed before the process becomes theoretically understood. The important reaction parameters must be defined, examined, and used to establish reactor requirements, and many system variables must be identified and studied. Economic studies must be made, and if large-scale systems are to be considered, the accompanying impacts on the community or region must be assessed.

The potential of biogas production from crop residues could be exploited in several modes. Farmstead reactors similar to the successful manure digesters are certainly possible. Small-scale operations at other locations appear feasible; a study I made of the potential for home heating, for example, indicated that my ten-room house near Ithaca could be heated for a year with biogas generated from a 4,000-cubic-foot reactor stocked with three



hundred dollars' worth of straw. But the most exciting possibility we have explored so far is the implementation of a community system with the capability of supplying a major part of the region's overall energy requirements.

An additional important possibility would be to apply the technology to the treatment of municipal garbage. Although there is considerable interest in recovering biogas from sanitary landfill, existing methods operate under the natural conditions—that is, slow gas production over a period of fifty years or more. Ways of enhancing the conditions have not been considered. Dry fermentation shows promise of being capable of stabilizing garbage in less than a year while producing as much as a third of the natural gas needed by a community. An additional benefit would be a reduction in the amount of land required for the sanitary landfill to about 5 percent of the area used with a conventional system. Also, dry fermentation would permit a recycling of humus matter and would eliminate leachate pollution.

In its relatively brief history, the United States has experienced two major energy transitions (see Figure 5) and is headed for another one as petroleum and natural gas supplies decline. The need for practical new sources of energy, available soon enough to help avert crisis, is obvious. Biomass is such a source. It has the potential of supplying more than $150 billion worth of energy before the year 2000, yet it is not receiving the support needed to expedite the necessary research and development. In 1979 the federal budget for work on biomass fuels was about $35 million. If an average of 3 quads (3×10^{15} BTU) of energy a year were generated from biomass between 1985 and 2000, the total value of this energy would be $135 billion. It would seem that a small fraction of this amount should be spent now and in the near future on research and development.

The strongest limiting factor in the development of technologies for converting biomass to fuel—and of other potential means of producing energy from renewable sources—is the lack of a national energy policy supported by the public. The economic impact of continued purchase by our nation of more than half the petroleum we use needs to be recognized and quickly dealt with. And as part of that effort, the potential contribution of small agricultural operations should be recognized and encouraged.

William J. Jewell, professor of agricultural engineering at Cornell, has concentrated his research efforts in recent years on the subject of this article—the use of agricultural wastes for energy production.

Jewell holds the B.S. degree in civil engineering from the University of Maine, the M.E. in sanitary engineering from Manhattan College, and the Ph.D. in environmental engineering from Stanford University. He came to Cornell in 1973 after serving as a postdoctoral research fellow in England and then teaching at the Universities of Texas and Vermont.

He is on the editorial boards of several professional journals in the fields of environmental engineering and water-pollution control, and he is active in a number of professional organizations.

Jewell, William J. "Removing toxic organics." *Cornell: Engineering Quarterly.* 1990_v25_n1 p. 25-29

REMOVING TOXIC ORGANICS FROM GROUNDWATER

Biological Conversion of PCE and TCE

by William J. Jewell

For over half a century, people have benefitted from the use of many chemicals whose impact on the environment remained imperfectly known. Among these chemicals are chlorinated solvents such as tetrachloroethylene (PCE) and trichloroethylene (TCE). These are excellent degreasing agents that have been widely used in industry and in the dry-cleaning business. They are not corrosive, not particularly flammable, and not highly toxic—in the short run. Unfortunately, they are associated with an increased incidence of cancer, and they remain in the environment for a long time.

Today, many such solvents are subject to rigorous regulation by the Environmental Protection Agency and are tolerated only in amounts that approach the limits of detectability. But the United States has been producing over ten million tons of chlorinated solvents per year since the early 1970s, with PCE and TCE accounting for about five percent of this total. The accidental discharge of only five gallons of these solvents can contaminate many square miles of groundwater, and thousands of different localities are already affected by billions of pounds of PCE and TCE as a result of improper disposal or accidental leakage.

TECHNIQUES FOR COPING WITH CHLORINATED SOLVENTS

Techniques presently used to keep PCE and TCE from contaminating groundwater involve vaporization or collection on materials such as activated carbon, which are then stored in special landfills designated for hazardous wastes. These are less-than-ideal ways to treat industrial waste water before discharge, and quite inadequate for cleaning up groundwater that is already polluted. In the first place, they do not really solve the problem because the pollutants are not broken down, but merely transferred from one environment to another. In the second place, these treatment techniques are expensive. Virtually all chemical companies, as well as numerous military bases and government laboratories, face billions of dollars in clean-up costs. Many companies have had to make strategic decisions about how much they can budget for clean-up without going bankrupt.

A better way to treat chlorinated solvents would be to break them down into harmless constituents. Many of humanity's traditional wastes are broken down by bacteria that occur naturally in soil and water. Such materials are said to be *biodegradable* (a term that is inappropriate for plastics that disintegrate without being chemically altered). Ten years ago, chlorinated solvents such as PCE and TCE were thought to be non-biodegradable. Recently, however, some microorganisms that can affect these compounds have been identified.

These microbes do not actually consume the chlorinated compounds, but use them in complex ways in the presence of another energy source, such as sucrose. Processes of this kind are referred to as *cometabolic*. The reactions that bring about the degradation of PCE and TCE are not yet fully understood, but it is useful to think of them as involving cometabolism, since the microbes must be supplied with all the nutrients required for growth while they attack the toxic materials.

DIFFERENT ROUTES TO BIODEGRADATION

In recent years there has been a national effort to identify new and more cost-effective technologies to purify industrial wastes and polluted groundwater. A number of research teams involved in this initiative have identified both anaerobic and aerobic bacteria that might play a part in the biodegradation of toxic materials. The anaerobic

Figure 1

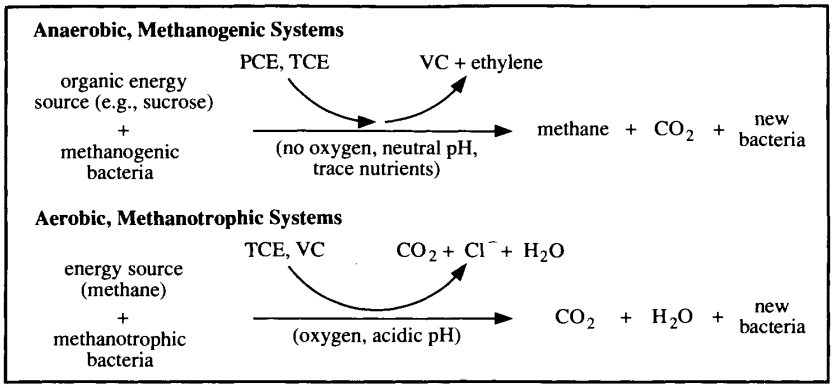
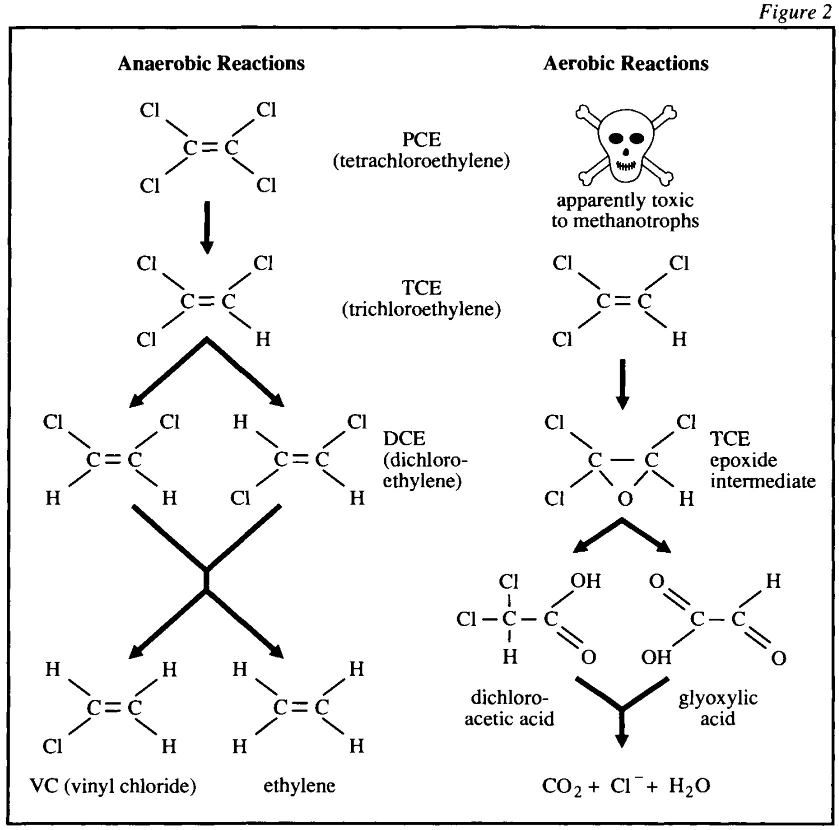


Figure 2



26

Figure 1. Anaerobic, methanogenic systems compared with aerobic, methanotrophic systems. Collateral pathways that degrade chlorinated solvents are shown with arcs tangential to the direct, metabolic pathways.

Figure 2. Collateral pathways that degrade PCE and TCE. The sequence of breakdown products formed in anaerobic systems is shown on the left, and products formed in aerobic systems are shown on the right.

bacteria produce methane, and hence are called *methanogenic*; in contrast, the aerobic bacteria "eat" methane and are called *methanotrophic*.

Some of the leading work on the mechanisms by which anaerobic bacteria dechlorinate PCE, TCE, and dichloromethane was done by James M. Gossett and David L. Freedman in Cornell's School of Civil and Environmental Engineering. In the absence of oxygen, these microorganisms convert complex organics such as sucrose to volatile acids, and eventually methane and carbon dioxide are formed. A collateral pathway breaks down PCE and TCE, producing vinyl chloride (VC) and ethylene.

The aerobic bacteria of interest inject oxygen into complex organic compounds. This leads to an instability that makes these compounds susceptible to the action of heterotrophic organisms, rendering them biodegradable.

Figure 1 compares the anaerobic, methanogenic and the aerobic, methanotrophic pathways for treating PCE and TCE. These sequences of reactions are not fully understood, but in both cases an energy source and an electron or an electron-donor source appears to be necessary

Many researchers were involved in developing the system for the methanotrophic biodegradation of TCE. Behind William Jewell are (from left to right) researchers Elaine C. Rawley, Yarrow M. Nelson, Brian K. Richards, Sean R. Carter, Fred G. Herndon, Timothy D. Nock, Mark S. Wilson, Robert J. Cummings, Lois J. P. Brown, Donna E. Fennell, and Evangeline V. Baradas.

to start the process. The focus of a project in which I am involved has been to understand the kinetics of both of these systems and evaluate their potential for breaking down chlorinated solvents.

Anaerobic and areobic processes both involve a direct pathway that sustains bacterial growth as well as a collateral pathway that affects chlorinated solvents (Figures 1 and 2). In the anaerobic process, chlorinated solvents are dechlorinated one step at a time, with PCE (whose molecule has four chlorine atoms) going to TCE (with three chlorine atoms), then dichloroethylene (with two), and finally vinyl chloride (with one) and ethylene (with none). The conversion to ethylene turns out to be a bottle-neck that limits the effectiveness of the whole process. Only a quarter of the dichloroethylene goes to ethylene; the rest becomes vinyl chloride, which accumulates in the system. This is not acceptable, since vinyl chloride is more volatile than PCE and TCE, and it is just as toxic—if not more so. Thus, anaerobic reductive dechlorination, by itself, is of limited value.

In contrast, aerobic pathways are shorter, but go to a more acceptable conclusion. Methanotrophic bacteria cannot attack PCE, which seems, in fact, to be toxic to them. Apparently, when all sites are occupied by chlorine, it is not possible for the enzyme, methane mono-oxydase, to inject oxygen into the molecule. But methanotrophic bacteria *can* attack TCE, converting it, through the addition of oxygen, into an epoxide intermediate. This is rapidly broken down into compounds that can be utilized by heterotrophic organisms that degrade it to carbon dioxide, water, and the chloride ion.

GETTING THE BEST OF BOTH WORLDS

Researchers in the Department of Agricultural and Biological Engineering have developed a highly effective attached-film bioreactor that uses what is known as an expanded bed. The bacteria in this reactor are attached to small granules, which makes it possible for them to interact with a flowing stream of water without being swept away. This is an obvious improvement over reactors that utilize bacteria in suspension.

Because of our expertise in this area, we were invited to participate in a nationwide effort—involving major universities, private consultants, and the Department of Energy—that seeks to identify a new, cost-effective technology for the biological treatment of contaminated groundwater. Our work is supported by the Gas Research Institute, an organization that represents the natural gas industry. Apart from having an interest in cleaning up contamination for which its members are responsible, the institute sees methanotrophic bioreactors as a possible new market for natural gas—which is more than 99 percent methane.

Figure 3

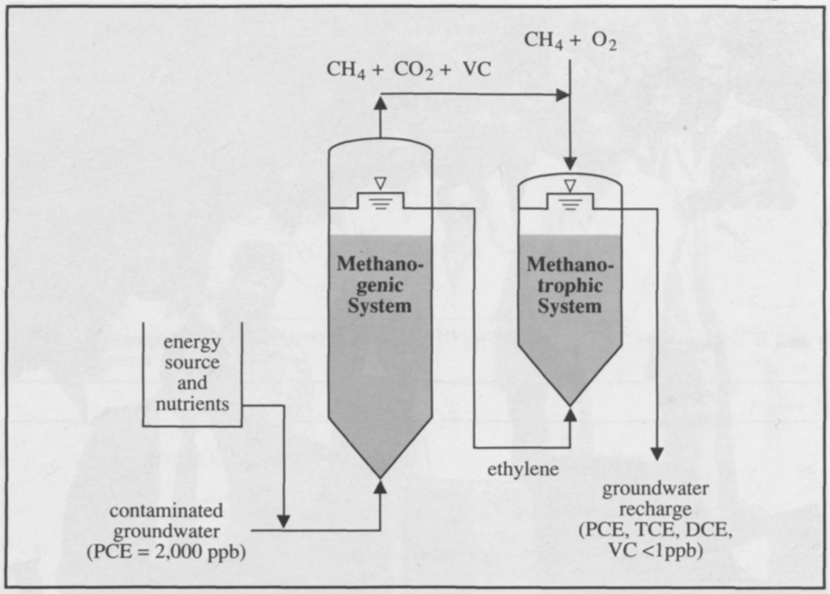


Figure 3. A hypothetical expanded-bed system for the biological treatment of common chlorinated solvents. Ratios of chemicals to water are given in parts per billion (ppb).

We began work on the project in 1987 and spent the first two years developing a methanotrophic attached-film expanded-bed (MAFEB) reactor. Because of the toxic nature of the materials involved, it was necessary to exercise extreme caution in testing and operation. Working with these materials is considerably more difficult than working with pollutants such as the organic materials found in sewage, and the cost of obtaining reasonable data is two or three times greater.

Our large team of researchers began by developing the methanotrophic kinetics for reactions involving TCE and its products at 35°C, and then began adapting the system to work at the ambient temperatures of groundwater. We found that the MAFEB reactor could utilize TCE at a rate approaching the maximum reported by microbiologists. This rate is relatively slow, however, especially when the TCE concentration is less than five hundred parts per billion.

At this point, a growing understanding of the kinetics of both anaerobic and aerobic systems sent us off in a new direction. We learned that anaerobic, methanogenic bacteria can not only degrade PCE (which methanotrophic bacteria could not), but that they are also able to degrade other, more highly chlorinated compounds more rapidly. This suggested the possibility of a hybrid system, with an anaerobic, methanogenic first stage followed by an aerobic, methanotrophic second stage.

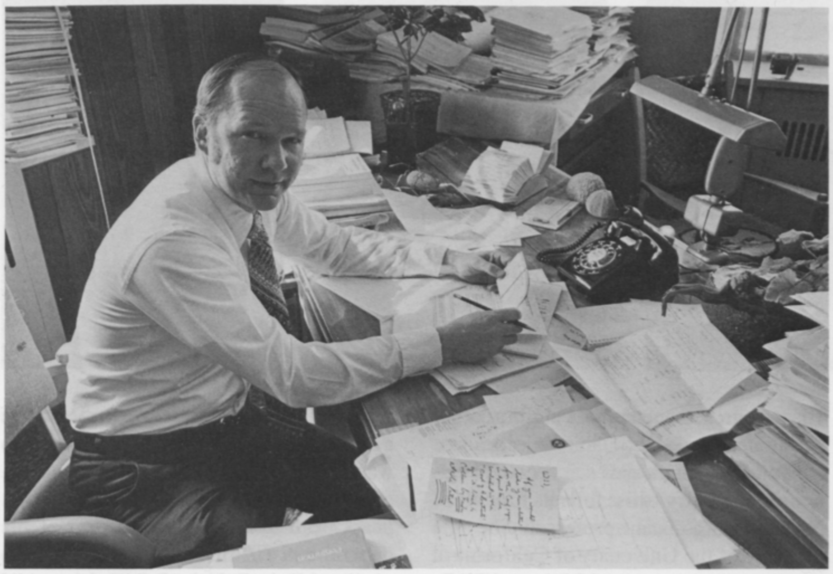
In August 1989 we began experimenting with an anaerobic attached-film expanded-bed reactor. After a short period of acclimation, anaerobic dechlorination occurred extremely rapidly and proved very efficient. Even without being optimized, the system was able to reduce the PCE concentration from 10,000 parts per billion to less than 50 parts per billion in a hydraulic retention time of under two hours. As expected, much of the PCE was broken down only to vinyl chloride.

This is where the aerobic system took over: the vinyl chloride was introduced into a second-stage, methanotrophic reactor. In early tests, the level of vinyl chloride was reduced to undetectable levels in a matter of hours.

FIRST STEPS TOWARD A PRACTICAL SYSTEM

The ideal way to conduct bioremediation of polluted groundwater would be to stimulate bacteria that are already present in the soil to degrade toxic materials. But when soil conditions do not provide the right environment for the bacteria, *in situ* treatment is not possible. Instead, an above-ground treatment system must be used. This involves pumping the polluted water up to where it can be treated, and then either returning it to the ground or discharging it.

The treatment process can be controlled much more easily in above-ground treatment than in an *in situ* operation. Because



of this, most researchers feel that initial experiments in bioremediation should be done above ground. Once a process is well understood, it may be possible to increase efficiency and reduce cost by adapting it for *in situ* application.

Our studies of the kinetics of reactions in attached-film expanded beds that utilize both anaerobic, methanogenic bacteria and aerobic, methanotrophic bacteria indicate that chlorinated solvents could be treated successfully with a hybrid above-ground reactor. The possibility of building a pilot model of such a reactor at the Department of Energy's Savannah River Laboratory in 1991 or 1992 is currently under review.

Meanwhile, the team at Cornell's Department of Agricultural and Biological Engineering continues working to define more precisely the limitations of the system. The speed with which this new technology is being developed is truly impressive. What seemed impossible just ten years ago may soon be demonstrated in the field.

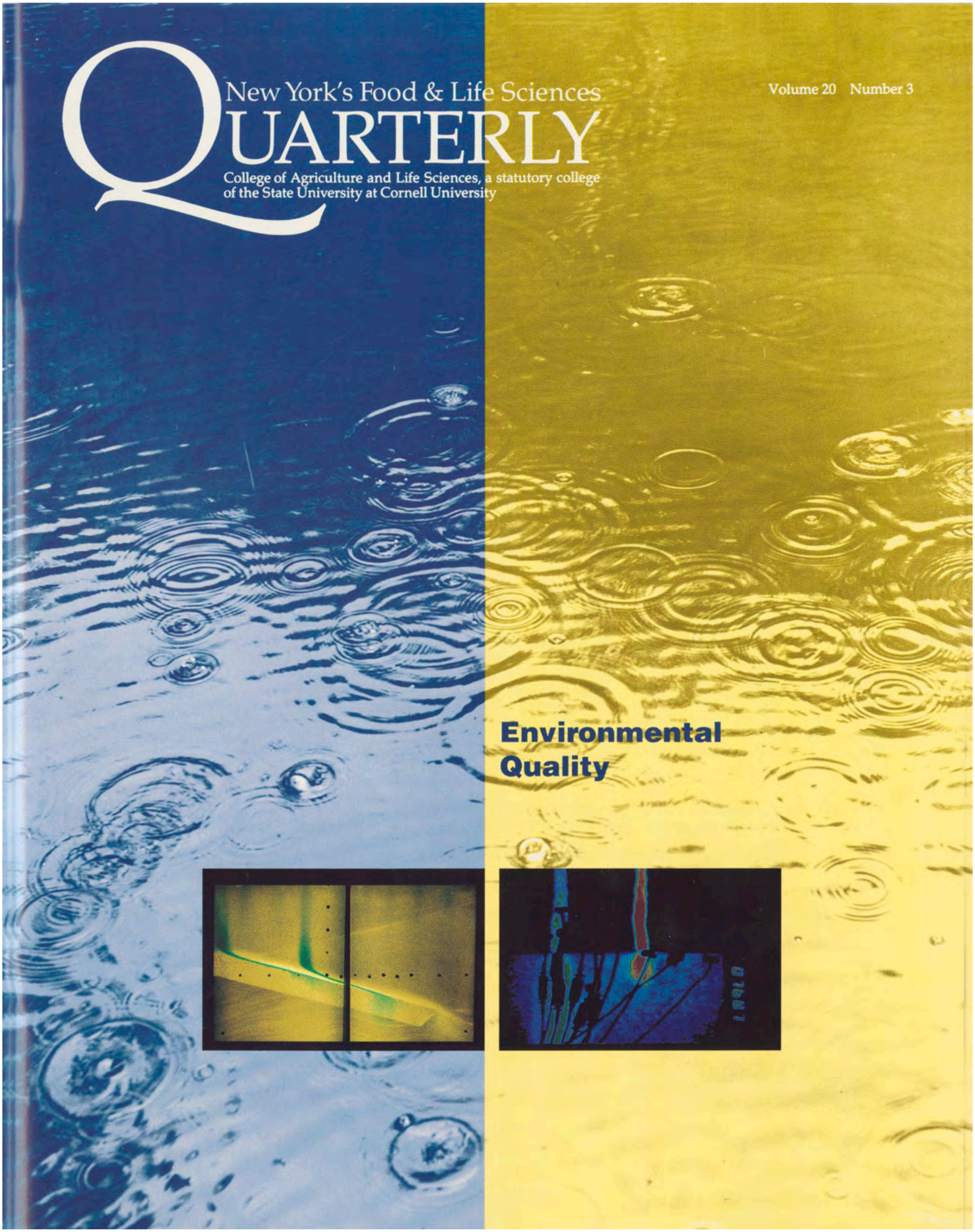
William J. Jewell is a professor of agricultural and biological engineering at Cornell.

Before joining the faculty in 1973, he earned the B.S. degree at the University of Maine, the M.E. at Manhattan College, and the Ph.D. at Stanford University; did postdoctoral research at the University of London and the Water Research Center in Stevenage, England; and taught at the University of Texas and the University of Vermont.

He has been a consultant to industrial firms, the Environmental Protection Agency, the U.S. Department of Agriculture, the United Nations, and several foreign governments. He belongs to a number of professional organizations in agricultural and civil engineering and has been active in their national committee work.

". . . chlorinated solvents could be treated successfully with a hybrid above-ground reactor."

Jewell, William J. "Land Application of Sludge Has Merits. *New York's Food and Life Sciences Quarterly*, issue on "Environmental Quality." v20_n3 p. 7-8 Vol.20. No.3. p.7-8.



Land Application of Sludge Has Merits

Sewage sludge is often viewed as nutrients "on loan" to city folks from farmers. This simplistic view of the beneficial aspects of sewage sludge has been reinforced by the many farmers who use stabilized and safe sewage sludges in agricultural operations.

While touring farms used as ultimate disposal sites for industrial sewage sludges around the city of London, England in 1969, it was clear to me that this was an acceptable and even desirable practice. To be sure that land was available for this purpose, each of the sewage plants owned their own crop production farm and did continuous testing with these sludges. The farms reported progressively increasing yields for many crops over the years that sewage sludge was used, and many of the farmers in the region competed to obtain sewage sludge for their particular operation.

Of course, the by-products of human activities also present in the sludges complicate the simplistic view of using the material as a fertilizer. The main three contaminants of concern to public health authorities are pathogens, heavy metals, and toxic organics. Any of these three components can reach concentrations that would prohibit the use of sludges on land. Regulations for the land application of sludge in the United States have been enforced at the federal level since 1979. There has been a great deal of on-going research and regulatory review since that time; the new regulations proposed in 1989 are scheduled for final promulgation in October 1991.

Sewage sludge must meet strict composition characteristics before it can be applied to agricultural and forage land. In general, the requirements limit the heavy metal contents, the toxic organics, and the attractiveness of the sludge to such disease vectors as flies, mosquitoes, and rodents.

If the sludge meets the composition criteria for heavy metals and toxic organics, it must be treated by technologies referred to as PSRPs—"Processes to Significantly Reduce Pathogens," or PFRPs—"Processes to Further Reduce Pathogens." In general, the PSRPs allow land application of sludge, but must incorporate access and use restrictions. The PFRP technologies are intended to reduce pathogens to below detectable levels. No site management restrictions are necessary when this treated sludge is land applied.

The Environmental Protection Agency (EPA) recently released a national survey of the level of contamination occurring in sewage sludges. A total of 209 treatment facilities were sampled (in several cases, in more than one area). Many classical materials, such as the total organic nitrogen, phosphorus, cyanides, and so forth, were assayed as well as 69 metals and 330 different organic compounds. In general, most organic compounds were not detected regularly and are not considered a problem for land application. Likewise for the majority of sludges, their heavy metal composition would not represent a limitation.

The relationship of the metal concentrations observed in the national survey to the concentrations acceptable with a relatively high loading of sludges is shown in Figure 1.

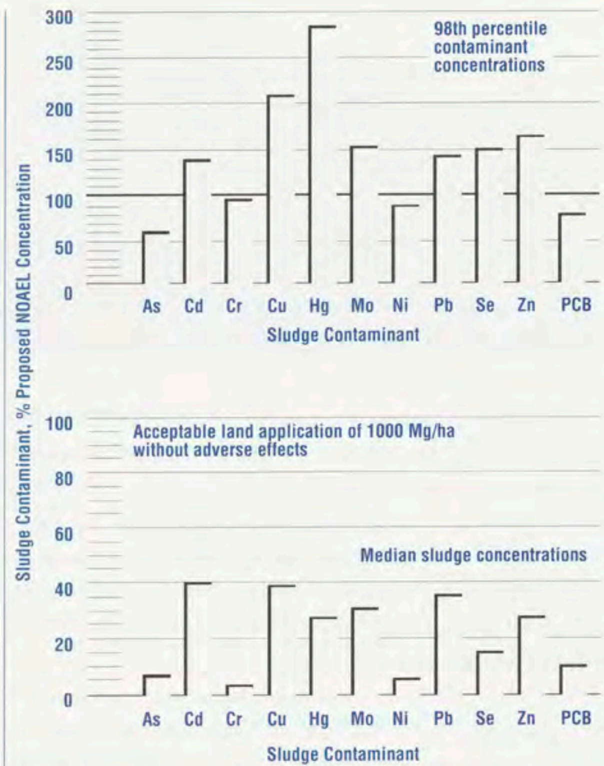


Figure 1. Comparison of sludge composition as observed in the recent national survey to a hypothetical sludge that would produce "no observable adverse effects" at a land application rate of 1,000 mt (dry)/ha.

For more than half the sludges, none of the contaminants exceeded acceptable levels as defined by the lack of any observable adverse effects. For sludges originating in the more contaminated regions (98 percentile), some of the metals exceed acceptable levels for the application of 1,000 metric tons of dry sludge per hectare (about 398 tons/acre). This suggests that the nutrient requirements for many plants could be satisfied for over a 10-year period with sewage sludge without any adverse effects from the metals of concern.

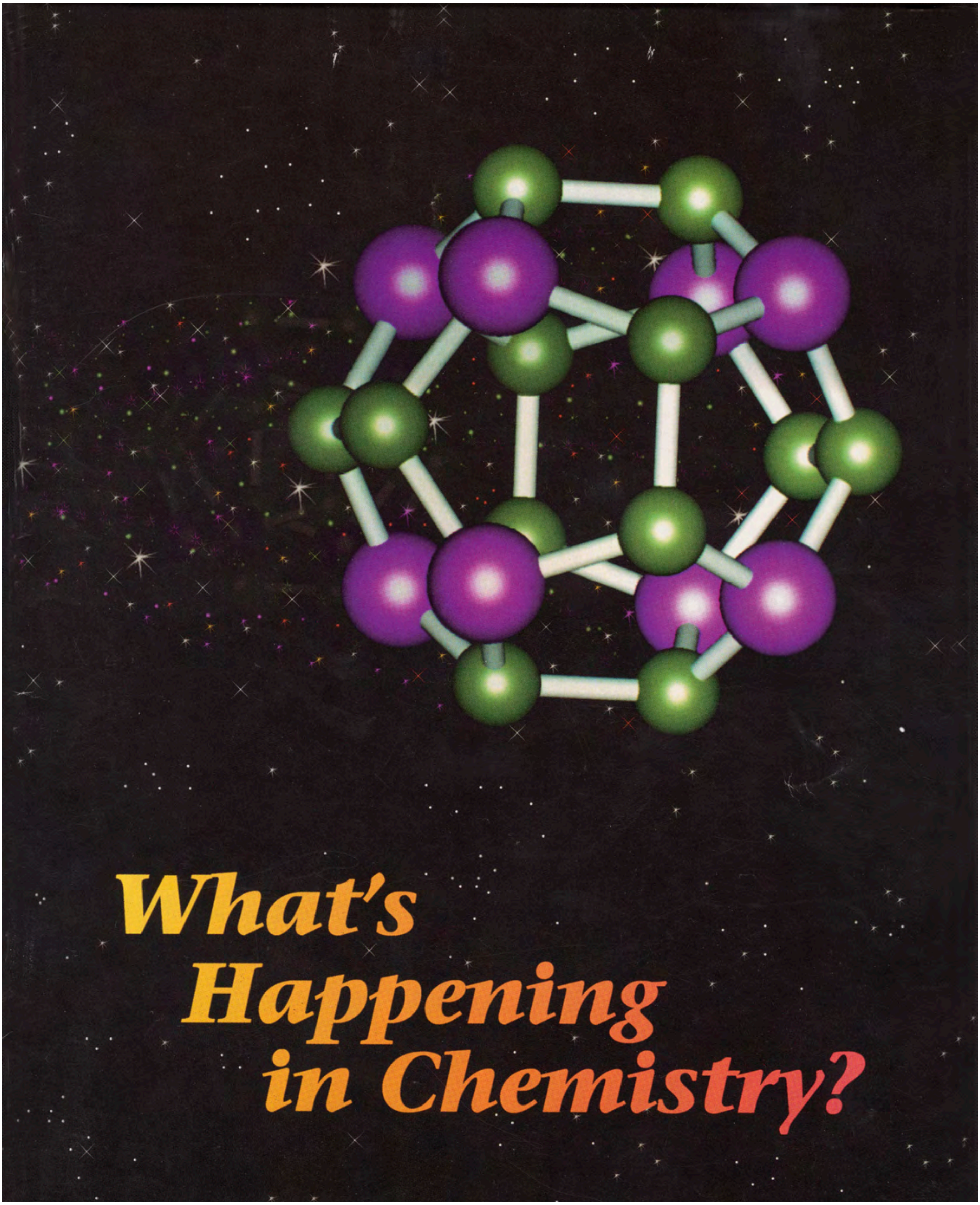
Members of our Department of Agricultural and Biological Engineering have been involved in teaching, research, and extension activities related to sludge application to land for several decades. My work has focused on the control of pathogens and heavy metals. When Cornell's Animal Science Teaching and Research Center was constructed in 1970 at Harford, New York, a full-scale, experimental system, referred to as "liquid composting," was constructed as part of the center's waste management facilities. Cornell University was the first to document this technology after it was introduced in Germany in the early 1970s. This technology employs highly efficient aerators that conserve the energy of oxidation of organic matter to produce an autoheating effect, raising the temperature of liquid slurries as high as 150°F (65°C) without using any supplemental heat energy. This results in high stabilization rates as well as weed seed and pathogen destruction. Following the research on animal waste, this process was studied for application to sewage sludge treatment. Using this technology it has been shown possible to create temperatures with sewage sludge that would effectively pasteurize the sludge and eliminate the pathogen problem. Additionally, our work has developed cost-effective means of removing heavy metals from sludge. The main metal of public health concern, cadmium, can be removed down to concentrations approaching background levels found in materials such as cow manure. Further, it is possible that these metals could be concentrated and recycled back into industry. Where toxic organics are not present, the Cornell University sludge detoxification process can convert sludges into organic materials that are considered safe for land application.

Today, the "liquid composting" technology is being rapidly commercialized in Europe. There are two full-scale facilities in Canada, and one planned in the United States. This technology appears to be the most cost-effective sludge stabilization alternative today, and is especially applicable to small, rural situations.

Existing information and technologies for sludge treatment enable sufficient quality control to protect health and the food chain in land application of sewage sludges. We do not advocate land application of sludge as a panacea, even though there are many applications where it could be beneficial. It should be emphasized that the amount of sewage sludge currently available is a relatively small quantity and could be totally consumed in reestablishing vegetation on damaged or disturbed lands. These may be the places where the fertilizer "on loan" to us in the food chain would be most beneficial.

—*William J. Jewell*
Agricultural and Biological Engineering

—— "Bioremediation Could be Answer to Superfund Clean-up. [American Chemical Society brochure, "What's Happening in Chemistry", highlighting five most important research topics—featuring Jewell's work. p. 50-52.



Bioremediation Could Be Answer to Superfund Clean-up

Scientists at Cornell University have enlisted Mother Nature in the battle against environmental pollution. They have developed the first known system that completely transforms toxic chlorinated contaminants in groundwater into ordinary salt, carbon dioxide and water.

The system is one of the newest applications of bioremediation, a technique that uses bacteria and other micro-organisms to accelerate the breakdown or degradation of toxic chemicals, heavy metals, oil spills and other environmental contaminants.

> "BIOREMEDIATION HAS QUIETLY BECOME A PROMISING ALTERNATIVE TO MORE CONVENTIONAL TECHNOLOGIES FOR CLEANING UP POLLUTANTS."

Bioremediation has quietly become a promising alternative to more conventional technologies for cleaning up pollutants. More than 8,000 scientific reports published on bioremediation during the last decade have helped move it out of the laboratory and into the field as a practical alternative to more conventional clean-up techniques.

Bioremediation was used extensively in the clean-up of the 1989 Exxon Valdez oil spill, for instance. Experts believe its importance will increase as scientists and policy-makers grapple with the clean-up of thousands of hazardous waste sites under the Federal Superfund and other programs. About 32,000 of these hazardous waste sites are being considered for such remediation work, which would attempt to remove contaminants from soil or groundwater.

William Jewell, the professor of agricultural and biological engineering at Cornell who developed the new bioremediation technique, believes it could have immediate practical application in the clean-up of groundwater at Superfund sites. The process is fast, efficient, works at low groundwater temperatures (when bacteria are less active) and can detoxify some of the most worrisome compounds. These include chlorinated industrial solvents such as trichloroethylene (TCE) and perchloroethylene (PCE). The compounds are common groundwater contaminants at hazardous waste sites. They are so toxic that U.S. Environmental Protection Agency (EPA) regulations permit only minute amounts—5 parts per billion (ppb)—in drinking water. Even a relatively small volume of PCE and TCE can make groundwater, the source of drinking water for millions of Americans, unusable.

Current remediation efforts underway for TCE and PCE involve pumping contaminated water out of the ground and using various techniques to remove the contaminants. Jewell says that these are far from ideal, since they produce another waste disposal problem. Once removed from the water, the contaminants themselves must be disposed, often in specially-designed landfills.

The bioremediation technology developed by the Cornell group, however, detoxifies compounds like TCE and PCE, making them harmless. Jewell says that the process can reduce the concentration of PCE, for example, from 10,000 ppb to less than 1 ppb—well within EPA standards for drinking water.

> "...IT COULD HAVE IMMEDIATE PRACTICAL APPLICATION IN THE CLEAN-UP OF GROUNDWATER AT SUPERFUND SITES."

> **"As the microbes metabolize or 'digest' the pollutants, they also detoxify them."**

In developing the process, Jewell and his associates drew on the work of other scientists, who identified bacteria capable of metabolizing and detoxifying TCE and PCE.

Scientists conducting research on bioremediation have found that a variety of bacteria and some fungi naturally consume environmental pollutants. As the microbes metabolize or "digest" the pollutants, they also detoxify them. Oil-degrading bacteria, for instance, use enzymes to break down crude oil into harmless byproducts. Certain fungi in the soil can consume selenium, burping out a harmless gas known as dimethylselenide. Selenium is a non-metallic trace element, essential for health in minute amounts but toxic at the high levels existing in some agricultural wastewaters.

Bioremediation researchers are trying to find ways to speed the growth of natural bacteria that consume such pollutants. They also are attempting to identify and enhance the function of natural pollutant-degrading genes in such microbes. One possibility is to use genetic engineering techniques to create armies of pollution-crunching microbes with enhanced abilities of degrading toxic contaminants.

The Cornell biodegradation process uses a small bioreactor that fits on the back of a truck and can be transported to contamination sites. The reactor is essentially an incubator for bacteria. It incorporates special technology developed by Jewell and his associates that keeps bacteria firmly attached to small granules on a polymer film. The approach prevents bacteria from being washed away as contaminated water flows through the reactor's chambers. It also increases efficiency by exposing a larger surface area of bacteria—10,000 times more than other processes—to the water.

Contaminated water entering the bioreactor first flows into a chamber containing anaerobic bacteria, which live in the absence of oxygen. They dechlorinate TCE and PCE, stripping away chlorine and breaking down the compounds into vinyl chloride (which itself is toxic). The biodegradation process continues as the water flows into the reactor's second chamber, which contains aerobic bacteria. These bacteria, which must have oxygen to live, complete the degradation process to salt, water and carbon dioxide.

Both treatment stages use "co-metabolic-like" mechanisms to enzymatically break down the

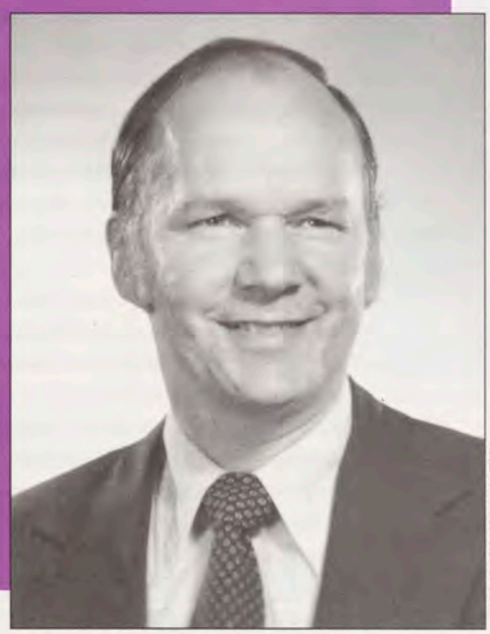


PHOTO COURTESY OF WILLIAM JEWELL

Cornell University professor William Jewell believes the new bioremediation technique he developed could be used to help clean up Superfund sites.

"... WE BELIEVE THAT OUR SYSTEM HAS THE GREATEST POTENTIAL OF ANY KNOWN SYSTEM ..."

chlorinated solvents. Although most bacteria prefer not to "eat" these chlorinated organics (and may not be able to use them as an energy source), they can be fooled into consuming these compounds if a much more desirable food is provided. Small quantities of sugar are added to the anaerobic process to enhance the dechlorination process. The second-stage aerobes consume methane as their energy source.

Importantly, the system works efficiently even when water temperatures are relatively low. As temperature decreases, bacteria are less active, and their metabolism slows. But studies have shown that the bioreactor continues to function well even at temperatures as low as 50 °F. Jewell says that the larger surface area of bacteria in the reactor compensates for the temperature-related declines in metabolic activity.

"As a result, we believe that our system has the greatest potential of any known system—it can remain small and cost-effective even in cold temperatures," Jewell notes.

Plans call for scaling up the reactor to a size capable of processing 40,000 gallons of contaminated water per day during pilot tests at a contamination site.

SELECTED REFERENCES

T. G. Zitrides, "Bioremediation Comes of Age." POLLUTION ENGINEERING. Vol. 22, May 1990, pp. 59-60.

U.S. Congress, Office of Technology Assessment, "Bioremediation for Marine Oil Spills—Background Paper." U.S. Government Printing Office, Washington, D.C., 1991.

Philip H. Abelson, "Remediation of Hazardous Waste Sites." SCIENCE. Vol. 255, February 21, 1992, p. 901.

W. J. Jewell, S. R. Carter, D. E. Fennell, Y. M. Nelson, T. D. Nock and R. J. Cummings, "Methanotrophs For Biological Pollution Control: TCE Removal and Nutrient Removal With The Expanded Bed." GAS RESEARCH INSTITUTE ANNUAL REPORT. 1989 and 1990.

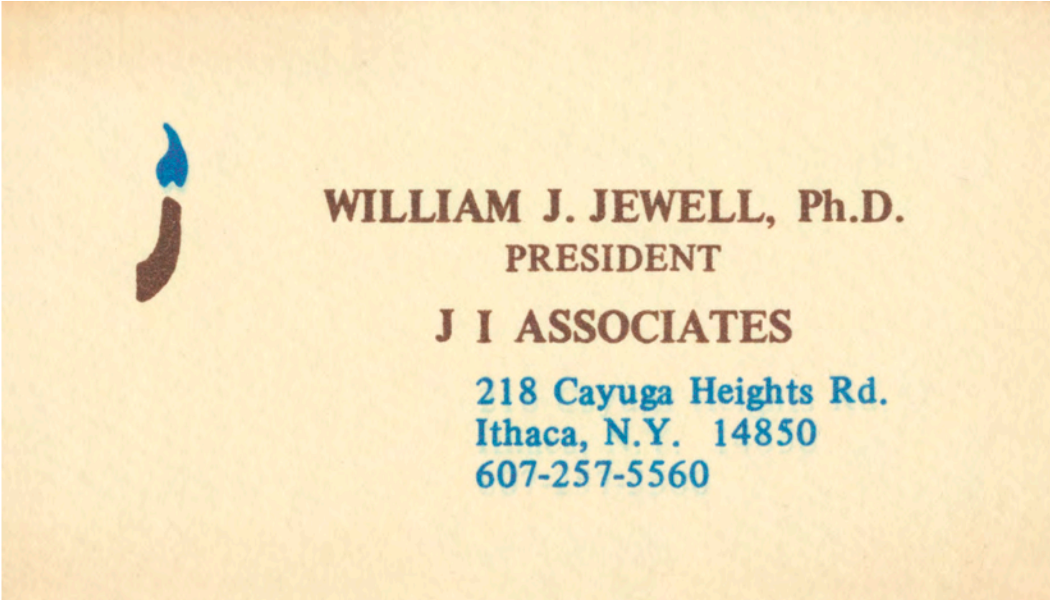
S. R. Carter and W. J. Jewell, "Biotransformation of Tetrachloroethylene by Anaerobic Attached Films at Low Temperatures." JOURNAL OF WATER RESEARCH. Vol. 27, 1993, pp. 607-615.

D. E. Fennell, S. E. Underhill and W. J. Jewell. "Methanotrophic Attached Film Reactor Development and Biofilm Characteristics." BIOTECHNOLOGY AND BIOENGINEERING. Vol. 40, 1992, pp. 1218-1232.

For further information
William J. Jewell
Department of Agricultural & Biological Engineering
Riley-Robb Hall
Cornell University
Ithaca, NY 14853-5701
Telephone: 607-255-4533

B. Brochures

First business card, 1977



JI Associates' first business brochure

J I ASSOCIATES, INC.

Box 100
South Berwick, Maine 03908

PRINCIPALS

President
William J. Jewell, Ph.D.

Secretary-Treasurer
S. William Ireland, B.S., E.E.

Founded in 1976

BACKGROUND

Clean renewable energy production, conservation of energy and environmental quality enhancement are essential tasks for mankind today. The basic operating principle of JI Associates is to make these tasks complimentary through the application of unique but tested solutions.

New technologies of JI Associates that have recently reached the commercialization stage hold promise of solving such pressing problems while contributing new sources of energy, increasing employment opportunities, and aiding the agricultural community.

The major focus of the firm's near term activities is the application of the Jewell process, a new biological treatment process that purifies wastewaters while producing a substitute natural gas (technical reference; the attached mircobial film expanded bed process).

GENERAL CAPABILITIES

The areas of operation and their potential markets are as follows:

TECHNOLOGY AREAS	MARKET (number of potential Applications)
1. Purification of waste-waters using an energy production process - Anaerobic Attached Film Expanded Bed - The Jewell Process	Municipal only new - 400 units retrofit - more than 10,000
2. Small Farm Biogas Generators	2 million +
3. Dry Anaerobic Fermentation for community scale substitute natural gas and alcohol production	1000 +
4. Biodryer recovery of wasted organics	5000 +
5. Microprocessor/ minicomputer design	(for above)

ENERGY OR RESOURCE MARKETS AFFECTED

1. Jewell Process	More than $2 billion worth of energy conserved and produced per year
2. Small Farm Biogas Systems	More than $3 billion per year of energy
3. Dry Anaerobic Fermentation	10% of U.S. energy supply
4. Biodryer	Food residue recovery of more than 10 million tons per year

The principals of JI Associates are either the inventors, have built the first sizeable unit, or implemented a facility.

PROJECTS

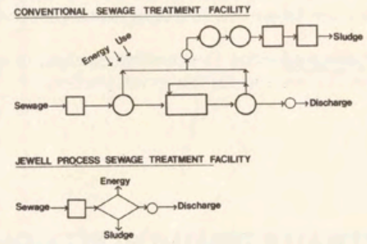
In the past, JI Associates has conducted feasibility studies for implementation of energy production systems for animal feedlots, food processors, and several communities. The Jewell Process has been recommended for treatment of sewage in two communities, and plans for implementation are underway. Agreements to implement the technology in Europe are presently being arranged with two firms in the United Kingdom.

A clean renewable fuel center concept using agricultural by-products to provide large amounts of natural gas and liquid fuels has been outlined in a $2.3 million proposal to the U.S. Department of Energy.

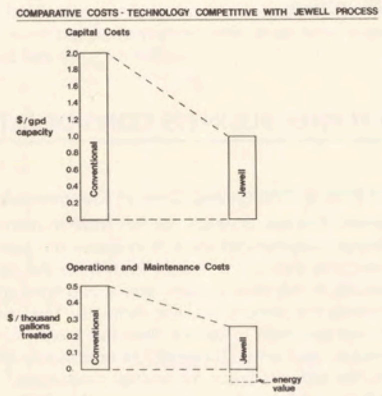
JEWELL PROCESS BACKGROUND

The Jewell Process was conceived in 1973, piloted in 1974 with sewage, and has been continuously researched to the present. It was the primary reason for initially organizing JI Associates in 1976. Today, two communities in the U.S. have formally requested implementation of the process, and several large companies in the United Kingdom and Europe have initiated discussions to use the process. Contracts for the first full scale units could be completed by mid summer of 1980.

The Jewell Process treatment plant compared to a conventional alternative in the following schematic shows the simplicity of the energy producing method of wastewater treatment.



Overall costs reduction of capital and operation and maintenance are illustrated below:



ECONOMICS OF THE JEWELL PROCESS COMMERCIALIZATION

Purification of sewage with the simultaneous production of energy was first shown to be possible by Dr. William J. Jewell through his development of the Jewell process. JI Associates believe its extensive use will have the greatest impact of any effort in the history of water pollution control. Its energy conservation and generation alone exceeds $2 billion yearly in municipal wastewater treatment. JI Associates' studies of sugar, brewery, and milk processing facilities have shown that between 10 and 90 percent of the energy needs of such industries can be generated during waste purification.

The following provides an economic analysis of alternative commercial programs for the Jewell process.

WASTEWATER TREATMENT ECONOMICS AND THE POTENTIAL MARKET

Although conventional treatment costs are process and site specific, recent analysis show that the capital costs of a facility would be about $2 per gallon of processing capacity. Since the Jewell Process is designed to control major pollutants (organics, suspended solids, nitrogen) and sludge quantities, it greatly decreases capital, operation and maintenance costs.

PRO FORMA BUSINESS CONSIDERATIONS

Jewell Process Design and Costs of Commercialization

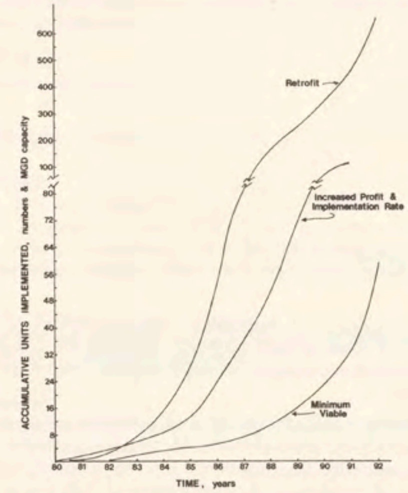
The Jewell Process is ready for full scale implementation. The design assumptions used to estimate the cost of implementation include: a reactor four times the size shown to be needed in the pilot studies, and a construction cost of 2 to 10 times the present realistic estimate. The cost to the buyer was assumed to be less than the lowest cost option by 40 percent, and only 20 percent of commonly adopted processes. No value is taken for energy production. A continuing service agreement is assumed equal to 14 percent of the total costs of operation of sewage treatment facilities.

Four main commercialization options have been examined:

1. Minimum viable form
2. Effects of increased rate of unit implementation
3. Increased profit margin
4. Retrofit program

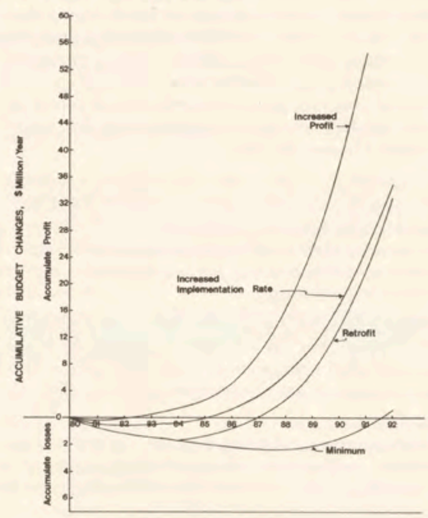
COMMERCIALIZATION RATE

The estimated rates of implementation are shown in the following:



PROFITS AND LOSSES

The net change in gross income and cost of operation is illustrated below for the four programs. Each of the following represent projected performance with initial total capital investment of less than $3 million.



EXPERIENCE

The two principals of JI Associates combine 34 years of technology research and development, business, and consulting experience in energy generation-pollution control-computer information management areas.

Dr. William J. Jewell, President, is an environmental engineering scientist with experience in microbial energy generation processes, biological waste treatment systems, land application of municipal and industrial residues, and development of high temperature organic residue recovery processes. He has held faculty positions at the Universities of Texas and Vermont, and is presently a Professor at Cornell University. Dr. Jewell is the author of more than 60 scientific articles and is listed in *"Who's Who in Engineering."* He has served as consultant to prominent consulting firms in the pollution control-energy generation areas, and to a number of foreign governments.

Over the past decade, Dr. Jewell has attracted nearly $5 million of engineering research and development funds from federal, state, and private sources. These resources were used to challenge a number of energy generation/pollution control problems and resulted in fundamental definitive studies as well as commercialization of several new processes. This information serves as the background work necessary to support successful business efforts in the innovative technology areas.

Presently more than 5 U.S. patent applications are under consideration in Dr. Jewell's name, including one on the anaerobic attached film expanded bed process. After more than 70 years of pursuit of a microbial process that could treat sewage with the anaerobic methane fermentation process, the Jewell Process has been shown to be a major breakthrough.

Mr. S. William Ireland, secretary-treasurer of JI Associates, is an electrical engineer and has 17 years of experience in the computer assisted information management areas. Mr. Ireland also has long term business experience in management of a million dollar recreational business.

Design, construction, and implementation of the newest micro-processor-mini computer technology is the specialty of Mr. Ireland. His most recent project involved custom development and implementation of a total community water supply reservoir monitoring/control system that involved three remote reservoirs.

BACKGROUND OF PRINCIPALS

The two principals of JI Associates have been closely associated since 1959 when they were roommates as undergraduate engineering students.

PRESIDENT

Dr. William J. Jewell

Born:

Waterville, Maine 1941, married

Education:

B.S. in Civil Engineering	1963 University of Maine
M.E. in Sanitary Engineering	1964 Manhattan College
Ph.D. in Environmental Eng.	1968 Stanford University
Postdoctoral Fellow	1969 University of London

Specialty Areas:

Innovative biological processes for energy production, pollution control, and resource recovery

Experience:

1973 to Present	Professor, Cornell University
1976 to Present	President JI Associates, Inc.
1970 to 1973	Associate Professor, University of Vermont
1969 to 1970	Assistant Professor, Univ. of Texas
1962 to Present	Consultant to industry, municipalities, major consulting firms, and foreign governments
	Author of more than 60 scientific articles, 3 books, member of numerous professional organizations and officer in many.

SECRETARY-TREASURER

S. William Ireland

Born:

Summers Point, N.J. 1941, married, 3 children

Education:

B.S. in Electrical Engineering 1964 University of Maine
M.S. Studies in Electrical Eng. University of Massachusetts
Short courses in computer design 1970-'80

Specialty Areas:

Design and construction of new microprocessor minicomputer systems for process and information management. Private business management.

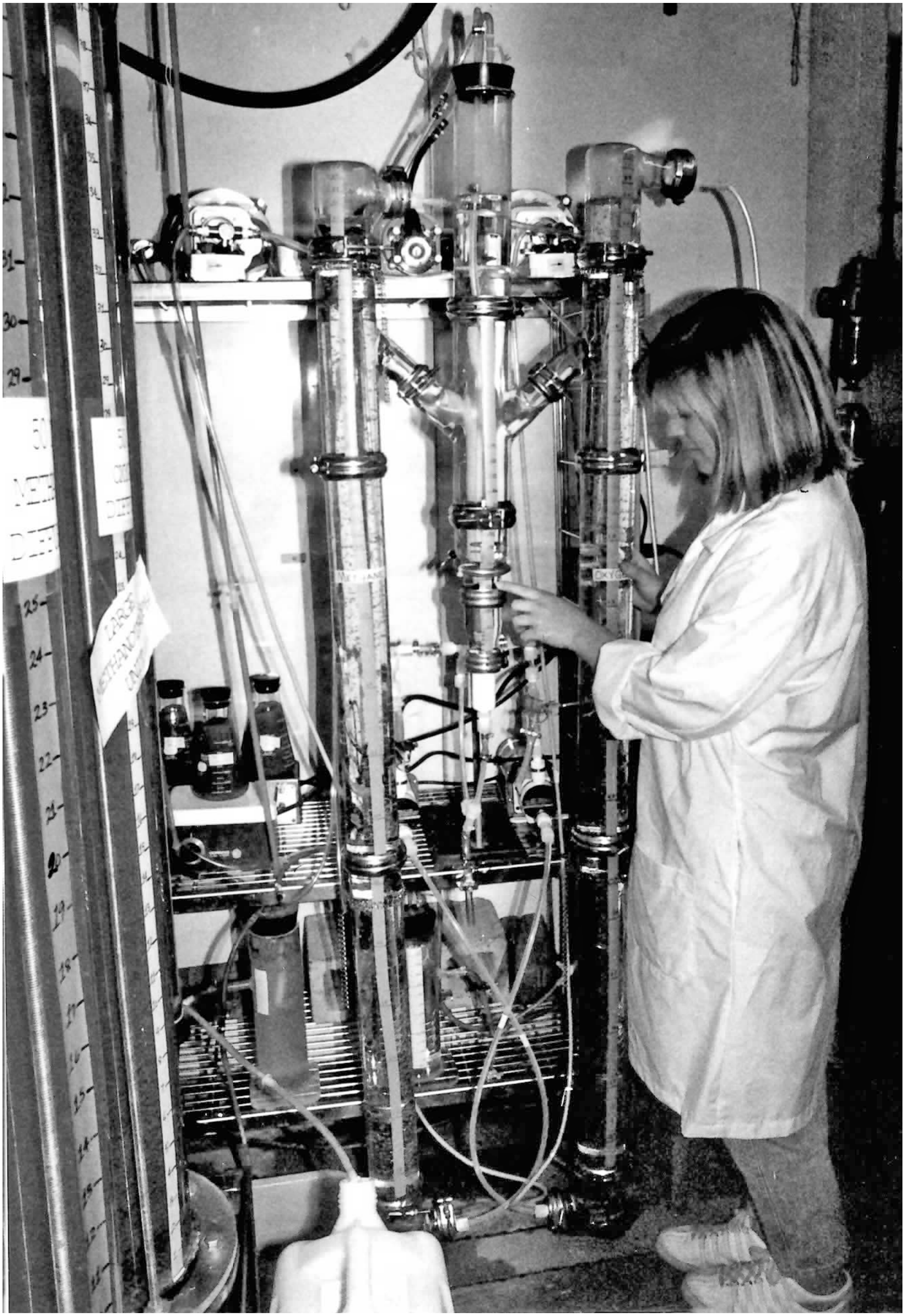
Experience:

1976 to Present	JI Associates Management
1974 to 1978	Owner/management of resort hotels
1964 to 1972	Project engineer in major computer companies, consultant to major industries

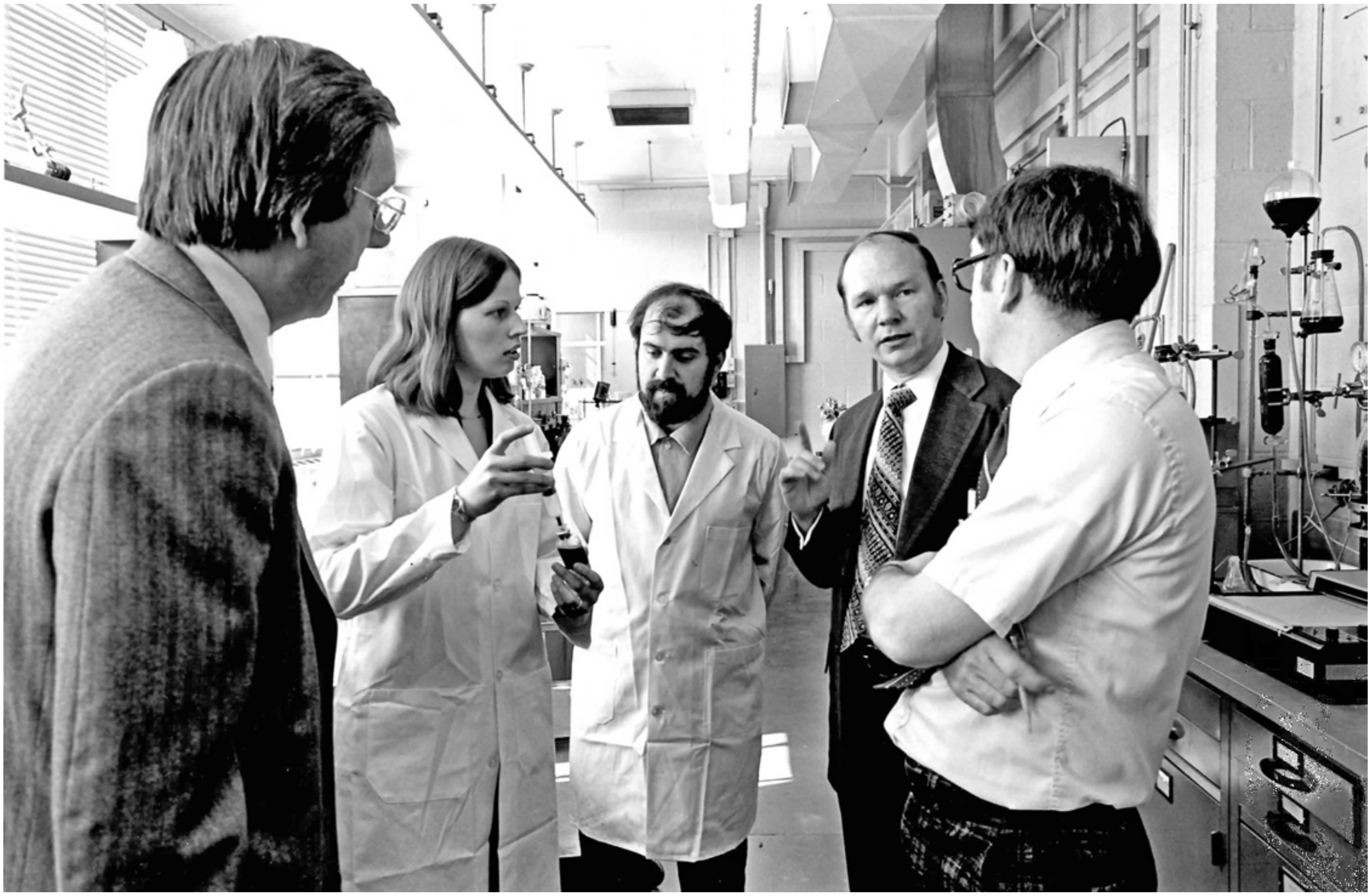
C. Photographs and Certificates

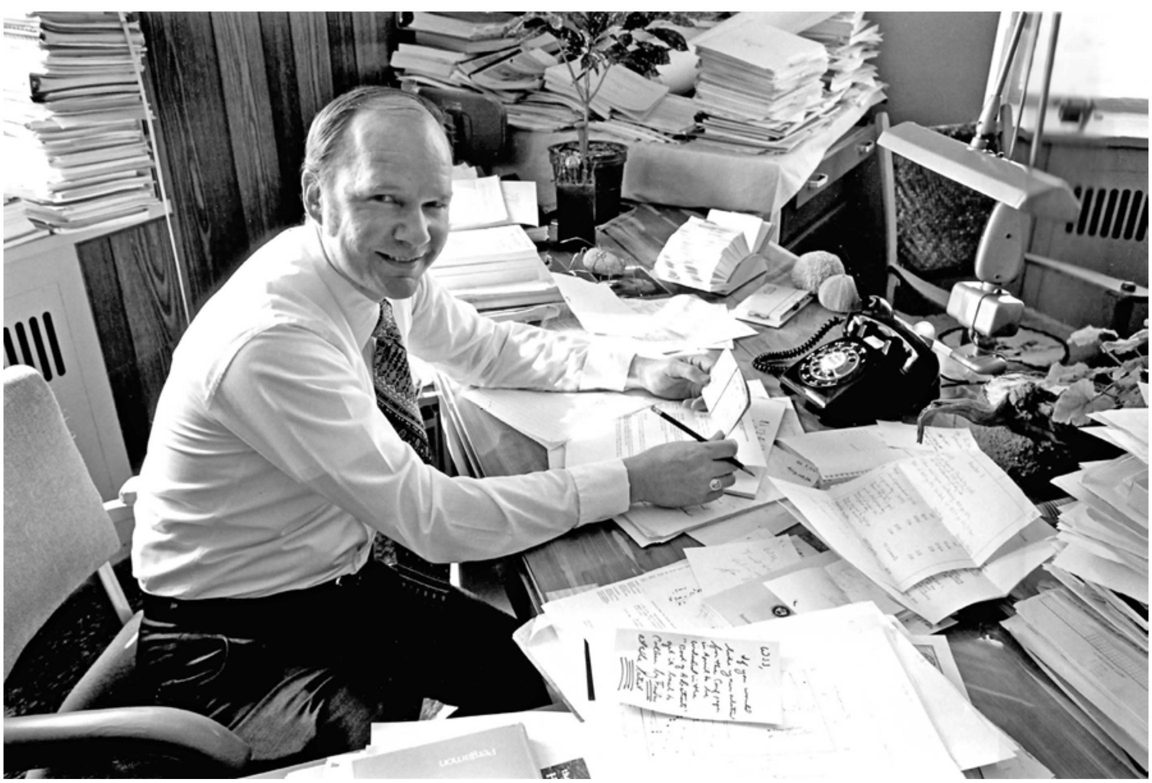
Jewell's team of researchers around the mid-90s. Three became professors, and two became heads of commercial high tech toxic remediation companies

Donna Fennell with biofilm reactors she was running to document chlorinated ethane bioremediation. Dr. Fennell is now a professor at Rutgers University.



Colleagues early in Professor Jewell's career: from left to right, Prof. R. C. Loehr, Patricia Dauplais, Research Technician, Michael F. Switzenbaum, Bill's first Ph.D. student, Bill, and Prof. D. C. Ludington.





Prof. W. J. Jewell's desk at Cornell was always neat and tidy.

The

AMERICAN SOCIETY OF CIVIL ENGINEERS

confers to

William J Jewell ,Ph.D.

Member

the status of

LIFE MEMBER

of the Society on

January 1, 2006

with appreciation for a lifetime of dedication and service to the profession of civil engineering

Patrick J. Natale
EXECUTIVE DIRECTOR

William P. Henry
PRESIDENT

Sigma Xi membership, Stanford University chapter, May 28, 1968

The Society of the Sigma Xi

Devoted to the Promotion of Research in Science

By this Certificate Warrants that

William James Jewell

was duly elected a member of the

Stanford Chapter

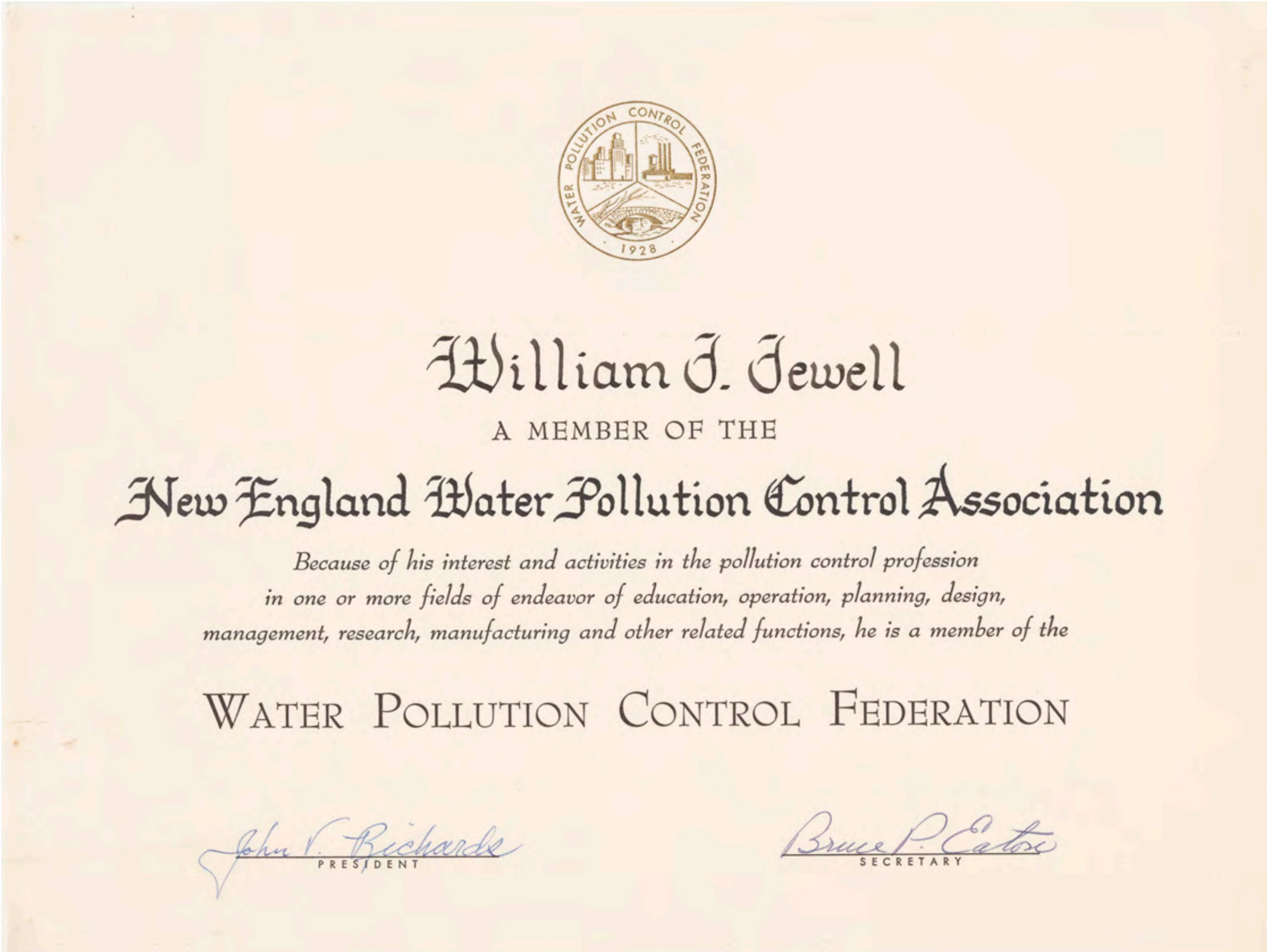
of

The Society of the Sigma Xi
on the 25th day of May, in the year 1968
and is fully entitled to all the privileges
granted by the constitution and by-laws

Carlton E. Schwerdt
CHAPTER PRESIDENT

Jeanette S. Brown
CHAPTER SECRETARY

Certificate of Membership in the New England Water Pollution Control Federation, undated



WATER POLLUTION CONTROL FEDERATION 1928

William J. Jewell

A MEMBER OF THE

New England Water Pollution Control Association

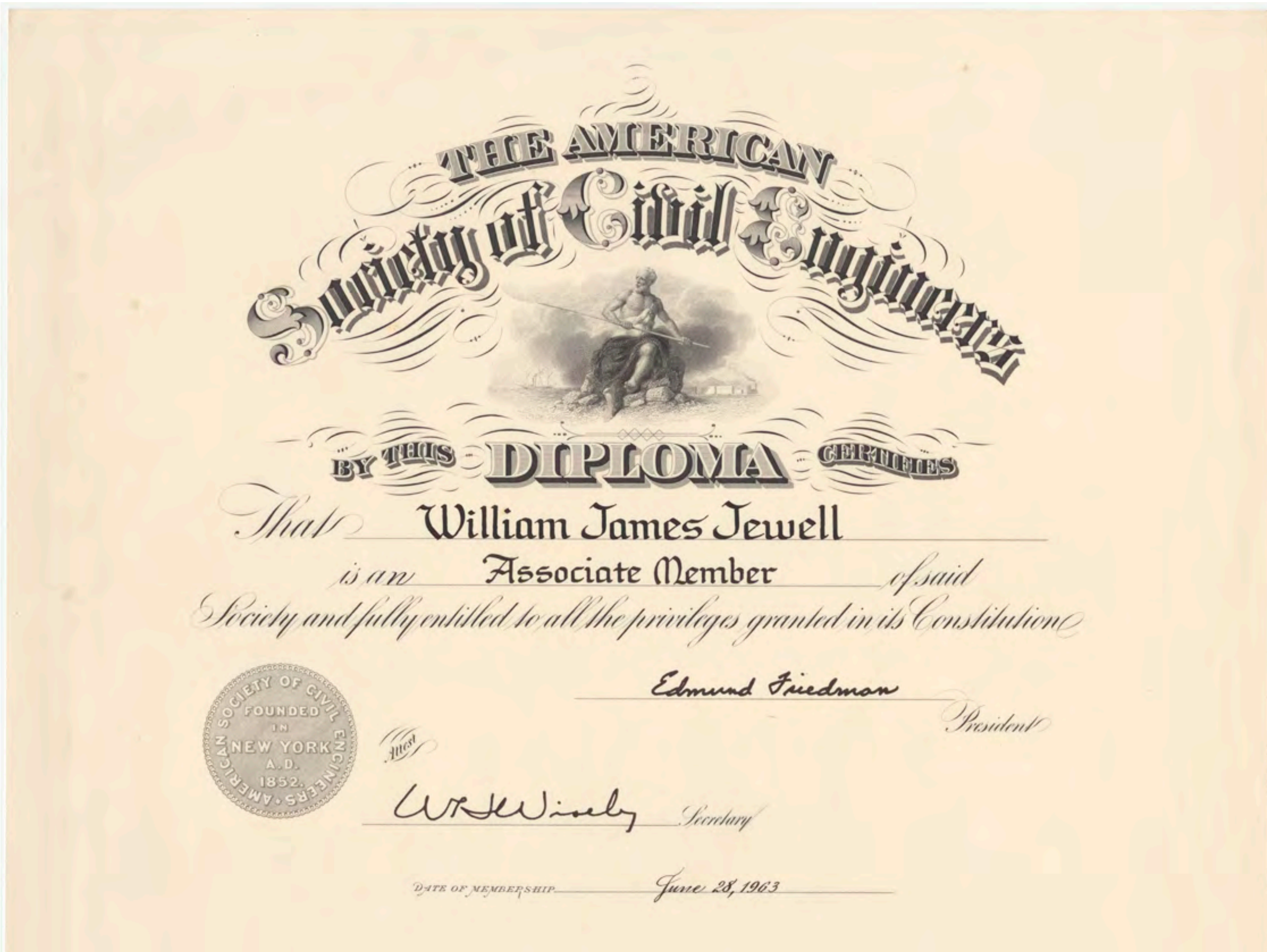
Because of his interest and activities in the pollution control profession in one or more fields of endeavor of education, operation, planning, design, management, research, manufacturing and other related functions, he is a member of the

WATER POLLUTION CONTROL FEDERATION

PRESIDENT

SECRETARY

ASCE Associate Membership 1963



THE AMERICAN
Society of Civil Engineers

BY THIS DIPLOMA CERTIFIES

That William James Jewell

is an Associate Member of said

Society and fully entitled to all the privileges granted in its Constitution

Edmund Friedman
President

AMERICAN SOCIETY OF CIVIL ENGINEERS
FOUNDED IN NEW YORK A.D. 1852.

Attest

W H Wisely Secretary

DATE OF MEMBERSHIP June 28, 1963

JI Associates stock certificate

NUMBER 2

SHARES 600

INCORPORATED UNDER THE LAWS OF THE STATE OF MAINE

J & I ASSOCIATES

The Corporation is authorized to issue 10,000 Shares Without Nominal or Par Value

This Certifies that Dr. William Jewell is the owner of Six Hundred (600)******************************** fully paid and non-assessable Shares of the above Corporation transferable only on the books of the Corporation by the holder hereof in person or by duly authorized Attorney upon surrender of this Certificate properly endorsed.

In Witness Whereof, the said Corporation has caused this Certificate to be signed by its duly authorized officers and to be sealed with the Seal of the Corporation.

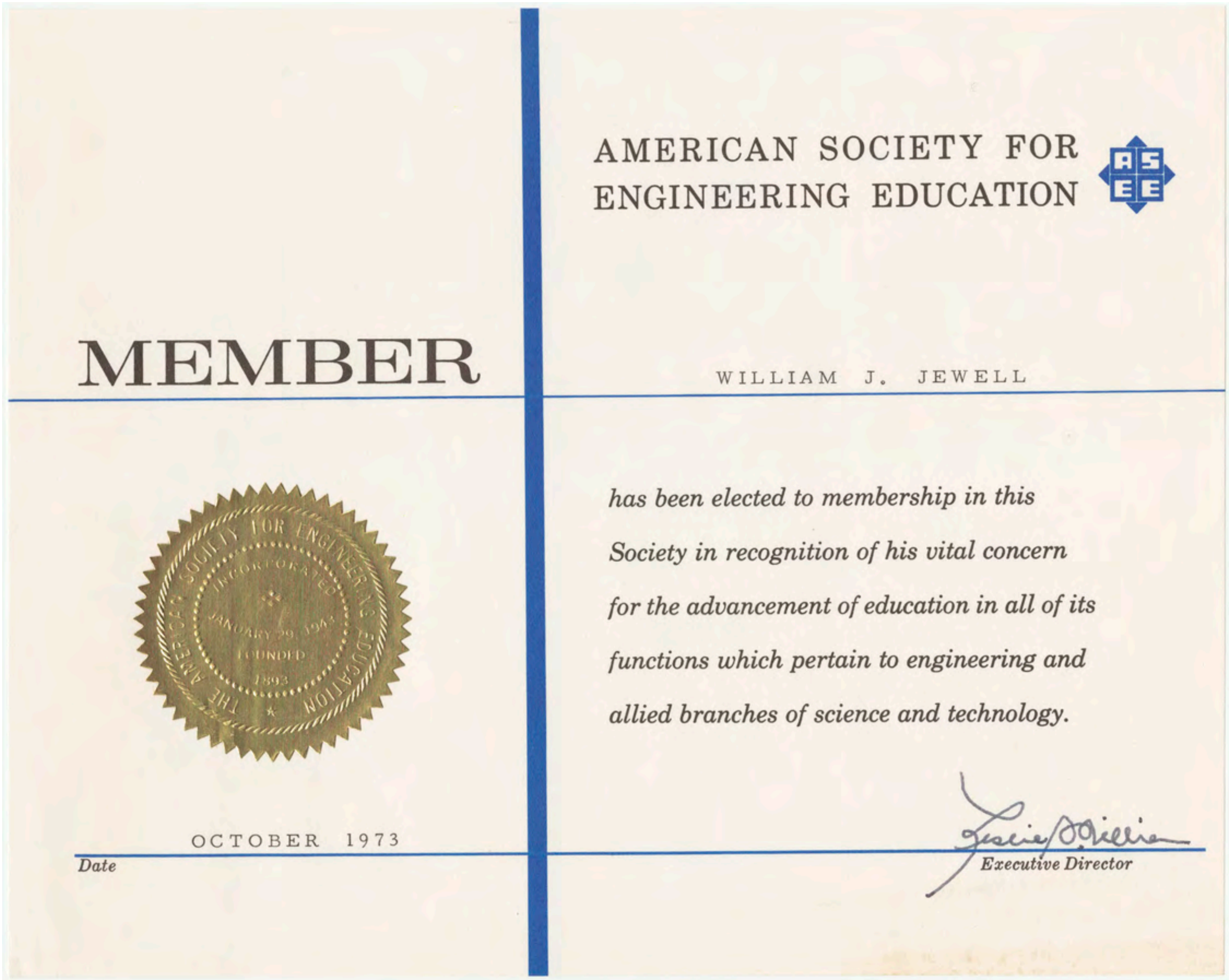
Dated January 31, 1977

TREASURER

PRESIDENT

EXCELSIOR-LEGAL STATIONERY CO., INC., 62 WHITE ST. NYC 10013

American Soiety for Engineering Education, October 1973



AMERICAN SOCIETY FOR ENGINEERING EDUCATION

MEMBER

WILLIAM J. JEWELL

has been elected to membership in this Society in recognition of his vital concern for the advancement of education in all of its functions which pertain to engineering and allied branches of science and technology.

OCTOBER 1973

Date

Executive Director

Jewell receiving the National Energy Award from the U.S. Department of Energy Secretary in 1988 in Washington, D.C.