FRANKLIN COUNTY SANITARY LANDFILL – LANDFILL GAS (LFG) TO LIQUEFIED NATURAL GAS (LNG) – PROJECT

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Table of Contents

Page

BACKGROUND AND INTRODUCTION 1

SUMMARY OF EFFORT PERFORMED 2

Task 2B.1 – Literature Search and Contacts Made 2

Task 2B.2 – LFG Resource/Resource Collection System – Project Phase One 3

Conclusion 5

Task 2B.3 – Technology Status – Conversion of LFG to LNG 5

Conclusion 7

Task 2B.4 – Economic Overview 8

Conclusion 9

Task 2B.5 – Post-Production On-site Storage, Dispensing, and Transportation Use of LFG to LNG 10

Task 2B.6 – Project Status 12

Conclusion 12

Appendix A – Summary of Applicable Literature
Appendix B – Franklin County Landfill Gas Flare Data
Summary of U.S. Landfills
Miscellaneous Project Data
Appendix C – LNG Conversion Factors
Appendix D – Renewable Fuels and CO_2 (Acrion Technologies, Inc.)
Appendix E – Landfill Gas to LNG and LCO_2 Final Report
Appendix F – SWACO Equipment as of July 13, 2004
LNG Tank Size and Weight Versus Diesel and CNG Tanks of Equivalent Fuel Gallonage

FRANKLIN COUNTY SANITARY LANDFILL – LANDFILL GAS (LFG) TO LIQUEFIED NATURAL GAS (LNG) – PROJECT

BACKGROUND AND INTRODUCTION

Degradable organic matter can be a significant source of non-fossil fuel based methane (CH_4). Methane captured from these "renewable" sources can be a feedstock for many applications including production of electricity, methanol, compressed or liquefied natural gas and others. One of the most intriguing and promising sources of biogas methane is landfill gas (LFG). LFG contains methane, carbon dioxide (CO_2), and other substances, some of which are toxic. Processes exist to strip CO_2 and other impurities from the CH_4 stream.

The Solid Waste Authority of Central Ohio (SWACO) operates the Franklin County Landfill, the 5th largest publicly owned landfill in the U.S. Within the last few years, SWACO installed a landfill gas (LFG) collection and flaring system. Now, they have secured a contract with Firm Green Fuels (FGF) to separate and capture valuable components of their LFG stream, including methane and CO_2. Under this contract, SWACO will provide 1,554 mmbtu/day of methane (project Phase One) to FGF for production of methanol. Another vendor is to use the methanol to produce biodiesel fuel on site.

SWACO also has requested that a small portion of the initial, "Phase One," stream be used to produce liquefied natural gas (LNG). Doing this would require additional equipment to liquefy a portion of this methane stream. LNG would be used to fuel a small number of LNG vehicles to be acquired by SWACO, pending available funding.

LNG is a good heavy-duty transportation fuel because it is very clean burning and has high energy content relative to its volume. It has proven successful in heavy-duty vehicle applications including sanitation trucks, transit buses, and tractor-trailers. Engines designed to operate on CNG also can use LNG. The upside potential of LFG to LNG is significant. These include cost savings for fleets, energy savings through a "high-end" use of a waste product, reduction of vehicle emissions including greenhouse gasses, hydrocarbons, NO_X, fine particles, and others, energy security through petroleum displacement, and local economic development.

The U.S. Department of Energy (DOE) has given NREL the responsibility to implement the Clean Cities Technical Assistance (Tiger Team) activity with the objective of providing assistance to Clean Cities Coalitions who are attempting to implement alternative fuels (AFs) and alternative fuel vehicles (AFVs) into their regions. The utilization of AFs and AFVs is intended to reduce the amount of imported petroleum used by the transportation industry, a primary objective of the Energy Policy Act of 1992. NREL is accomplishing this technical assistance by utilizing a team of competitively selected subcontractors who supply knowledge and expertise that is not currently resident at the Lab.

The Central Ohio Clean Fuels Coalition (COCFC) is a recently established (April 2002) Clean Cities Coalition based in Columbus, Ohio. Two significant opportunities have arisen in the Columbus area to implement AFs and AFVs, which can help to offset the use of imported petroleum and provide greater energy security, both objectives of the U.S. Department of Energy. These opportunities are 1) the utilization of AFVs at the Columbus airport and 2) the creation of LNG from landfill gas for use in local natural gas vehicles. The Columbus Airport

Authority and Solid Waste Authority of Central Ohio have each contacted the Director of the Central Ohio Clean Fuels Coalition, Sam Spofforth, to request assistance in planning these projects. NREL will be providing assistance to Mr. Spofforth in the implementation planning of AFs and AFVs at both of these sites. The data that is generated during the process of this technical assistance will be used by NREL to assist other Clean Cities Coalitions who are attempting similar approaches to increased use of AFs and AFVs in their regions.

This Letter Report addresses and summarizes the support assistance provided by NREL for item 2 above, the creating of LNG from LFG. This support was provided to Mr. Spofforth of COCFC. The support addressed resource/resource collection system, technology status for conversion of LFG to LNG, LNG storage/dispensing considerations, economic overview, and project status overview. This Report is intended to respond to the Tasks 1B, 2B and 3B requirements of NREL Task Order KLCI-1-31026-07B.

SUMMARY OF EFFORT PERFORMED

TASK 2B.1 – LITERATURE SEARCH AND CONTACTS MADE

The support provided by NREL to COCC on Tasks 1B, 2B and 3B was not intended to be exhaustive nor was there adequate funds to perform site and/or contact visits. The support was intended to be sufficient to assess technology status and an understanding of important economic factors. This information gathering was accomplished through an extensive literature search and selected phone contacts.

The literature search was conducted to understand available small-scale LFG to LNG liquefaction technologies, those involved in the development of the technologies, development/ commercialization status, system installations, and system economics. Appendix A presents a summary of applicable literature.

Review of Appendix A information provided a good summary of industry and research contacts that were interviewed by phone to update published information. Following is a list of contacted persons:

Name/Affiliation	**Contact Information**
Dr. James Wegrzyn Brookhaven National Laboratory	631-344-7917
William Brown Acrion Technologies	216-573-1185 acrion@aol.com
Steven Wilburn Firm Green Fuels	949-285-4567
Rick Dodge SWACO Franklin County Landfill	614-801-6402 rick.dodge@swaco.org
Michael D. Long SWACO	614-871-5100

Name/Affiliation	**Contact Information**
Bruce Smackey Mack Trucks	610-390-8240 bruce.smackey@macktrucks.com
Kent Stoddard Waste Management	813-909-0163
Sam Spofforth COCFC	614-292-5435 sam@cocfc.org
Ed Wheless, P.E. Sanitation Districts of LA County	562-908-4288, x2428
Martin L. Pomerantz, Ph.D. Business Development Group, Inc.	412-882-0184 pomerantzm@asme.org
William E. Liss Managing Director, Transportation Systems	847-768-0753 William.liss@gastechnology.org

TASK 2B.2 – LFG RESOURCE/RESOURCE COLLECTION SYSTEM – PROJECT PHASE ONE

SWACO, under Contract to Alcohol Solutions of Ohio, L.L.C. (now Firm Green Fuels), is to provide 1,554 mmbtu per day of methane for a period of 10 years. This methane is to be converted to methanol on-site and provided (sold) to another vendor who will produce and market biodiesel fuel. The methanol will also be marketed to industrial customers. In addition, SWACO has requested that a small portion of LFG be used to produce liquefied natural gas (LNG) during Phase One. SWACO requests that sufficient LNG per day be provided to fuel heavy-duty trash trucks (perhaps 16-20) to be acquired for landfill operations.

A Phase One LFG collection system has been installed. This system collects gas from approximately one-quarter of the landfill area. Collected gas is currently flared on-site. A check on minimum available LFG gas was made. Therefore, collection system flare data were requested of SWACO. Appendix B presents Franklin County Sanitary Landfill Flare Readings covering the period May 8, 2004 through July 7, 2004. A review of the data indicates daily, if not hourly, data variability. The data were reviewed to determine **minimum** methane content, gas flow and heat content. The following values were noted and were used for analysis performed for this study.

- Methane 56.4 percent
- Landfill Gas Flow 2,200 scf/m
- BTU Delivered 1,840 mmbtu per day

SWACO has, by contract, committed 1,554 mmbtu per day to the FGF/Acrion project. Therefore, there is approximately 286 mmbtu per day excess energy available for LFG to LNG conversion (1,840 mmbtu/day – 1,554 mmbtu/day). It is not clear whether the LNG required LFG is part of the Contract energy supply or in addition to the Contract requirement. It is assumed for purposes of this report's analysis, the LFG required to meet SWACO LNG requirements is in addition to the Contract requirements. Therefore, it is necessary to determine SWACO's LNG requirement for 16 to 20 trash trucks. Data provided were:

Trash trucks:	16 to 20
Mileage per year:	1/2 @ 75,000 miles/year
	1/2 @ 35,000 miles/year
Fuel Economy:	5 miles/gallon (diesel)
Days of operation:	300 (typical for similar analysis applications)
Minimum number of trucks:	20
Average miles/year/truck:	55,000 $\left(\dfrac{75{,}000 + 35{,}000}{2}\right)$

Therefore, annual fleet mileage is:

20 trucks x 55,000 miles/year = 1,100,000 miles/year

At 5 miles/gallon of diesel fuel, diesel fuel consumption is 220,000 gallons per year. A gallon of LNG has an energy content of 83,320 Btu. A gallon of diesel fuel has an energy content of 133,000 Btu. Therefore, a gallon of diesel fuel is the equivalent of 1.6 gallons of LNG.

$$\left(\frac{133{,}000}{83{,}320} = 1.596\right)$$

Thus, 220,000 gallons of diesel fuel per year is equivalent to 352,000 gallons of LNG per year. Based on 300 days of annual operation, this equates to approximately 1,175 gallons of LNG per day.

$$\left(\frac{352{,}000}{300}\right)$$

1,175 gallons of LNG per day x 83,320 Btu per gallon is 97.90 x 10^6 Btu per day or say 100 mmbtu per day. Thus, there is sufficient excess energy capacity available to fuel the 20 trash trucks (286 mmbtu/day vs 100 mmbtu/day). Should this requirement be included within the SWACO Contract commitment, it represents about 6.5 percent of the commitment.

$$\left(\frac{100 \text{ mmbtu/day}}{1{,}554 \text{ mmbtu/day}}\right)$$

If all excess methane energy capacity were converted to LNG

$\dfrac{286 \text{ mmbtu/day}}{83{,}320 \text{ btu/gal}} \approx 3{,}430$ gallons of LNG per day could be produced.

If all available Phase I methane were converted to LNG

$$\frac{1{,}840 \text{ mmbtu/day}}{83{,}320 \text{ btu/gal}} \approx 22{,}080 \text{ gallons of LNG}$$ per day could be produced.

CONCLUSION

There is adequate methane available from the Phase One collection system to meet Contract requirements and desired LNG production for 20 trash trucks per day. If all excess Phase One methane were converted to LNG, about 3,430 gallons of LNG per day could be produced. Should SWACO elect, based on market potential, to convert all available Phase One methane to LNG, about 22,080 gallons per day could be produced.

TASK 2B.3 – TECHNOLOGY STATUS – CONVERSION OF LFG TO LNG

Typical landfill gas properties are summarized by the following table.

Landfill Gas Properties	
Temperature, °F	70
Pressure, psia	14.7
Methane, %	54
Carbon Dioxide, %	45
Nitrogen, %	1
Contaminants, %	< 1
Water	Saturated

As indicated by the data summarized in Appendix B, these properties vary daily. The methane (CH_4) content of gas collected at the Franklin County Landfill is about 56.4 percent (as previously noted). The requirement is to efficiently, economically strip CH_4 out of the gas stream in order to utilize it as an energy resource. For this project, CH_4 is to be converted to methanol (CH_3OH) and LNG. It is the LNG product that is the Subject of this report.

LNG is typically generated in large-scale LNG plants with complex refrigeration processes and specialized equipment. Natural gas is the feedstock. Production capacities of about 15,000 tons per day are usual. The weight of a gallon of LNG is 3.6 pounds at atmospheric pressure and saturated liquid. This is at a liquid temperature of -259°F. As temperature changes, the liquid density (thus its weight) changes. These large commercial plants state production output in pounds (or tons) as a pound is constant and not subject to temperature/pressure variations. Appendix C presents typical LNG conversion factors. Please note data variability. Using 3.6 pounds per gallon yields approximately 8,333,000 gallons per day of LNG for the typical large-scale LNG production plant cited.

$$\left(\frac{15{,}000 \text{ tons x } 2{,}000 \text{ pounds/ton}}{3.6 \text{ pounds per gallon}} = 8.333 \text{ mm gallons}\right)$$

Large production capacity facilities produce product at a low cost per gallon (typically 35 to 45 cents per gallon with 53 cents per gallon as the price point) even though investment costs are high. LNG is also shipped to the United States and off-loaded at storage facilities for distribution. For small plants, the relative investment costs have been shown to be a major obstacle, especially if system efficiencies similar to large base-load plants are obtained. The Franklin County Landfill project would be a small system and cost-competitiveness may be difficult.

Small-scale LFG purification and liquefaction systems are under development by Acrion Technologies, Inc., GTI (Gas Technology Institute), and INEEL (Idaho National Engineering and Environmental Lab) and several foreign countries. Several of these systems have developed to the demonstration phase. **Demonstration projects have not achieved small-scale commercial system size to date.** Companies developing such technologies suggest that projects become cost-effective at a minimum production rate of 15,000 gallons of LNG per day. This production rate equates to 1,250 mmbtu per day. However, a review of the literature does not support this production rate conclusion and data are confusing at best. Small-scale appears to be a system producing less than 50,000 gallons of LNG per day. The critical equipment development item is the liquefier. Current liquefier development status suggests that LNG production rates less than 1,000 gallons per day should not be considered. The important finding is that no small-scale system has achieved commercial status to date. Each project is designed to meet demonstration goals. For small-scale systems, promising results have been achieved by the GTI and Acrion technologies. Based on the literature search and phone contacts, brief descriptions of selected small-scale technologies are presented.

The Pacific Gas & Electric/INEEL San Joaquin Valley project (planned for mid-2006) **expects to** deliver 20,000 to 30,000 gallons of LNG per day. They classify this project as a R&D, small-scale LNG liquefaction demonstration. The project budget is stated as $2.5 million. No system cost estimates for LNG production were provided. The liquefaction process requires high pressure supply gas and uses pressure letdown to accomplish the refrigeration/liquefaction.

A market study done for the GTI indicates that small-scale liquefaction is feasible in the 5,000 to 10,000 gallons per day production range with a unit costing about $500,000. GTI has developed a single-stage, mixed refrigerant, natural gas liquefier. This **prototype** unit, which has a capacity of up to 2,000 gallons per day, can be scaled to match feedstock flow and composition characteristics. GTI is designing a gas purification system for integration with the liquefier unit for processing pipeline quality feedstock, which does not have all the contaminants found in landfill gas. The capital equipment cost for this system is estimated to be about $350,000, with energy costs to operate the unit about $0.10 per gallon. Additional costs associated with purification of trace contaminants for landfill gas applications will increase capital and operating costs. This system addition is a must.

In order to be able to use landfill gas for natural gas vehicle applications or even for power generation (which is traditionally provided by pipeline gas), very high purity methane must be removed from the LFG supply stream. As carbon dioxide (CO_2) is a major component of LFG, it has been proposed that purification and liquefaction of CO_2 into a saleable product would improve the economics of developing LNG from LFG. The US DOE, through Brookhaven National Laboratory (BNL), has funded Acrion Technologies of Ohio to conduct a feasibility study on producing LNG and liquid CO_2 (LCO_2) from LFG. Using Acrion's patented, absorption process, which uses LCO_2 produced in-situ, they claim to recover more than 99 percent of the methane as usable product. **A pilot-scale system has been developed**. The study concluded that a landfill capable of providing sufficient LFG to produce 10,000 gallons of LNG per day (830 mmbtu per day) and 40 tons of LCO_2 per day could be economical. The economics depends upon the availability of suitable markets close to the source of production. Plant capital investment was estimated at $5.3 million with annual operating costs of $1.0 million. A summary description of the Acrion system is presented in Appendix D.

Acrion, under a US DOE, Phase II, SBIR grant, has been funded to develop a Process Demonstration Unit (PDU) which embodies their patented CO_2 Wash™ contaminant removal technology to produce clean methane (75 percent methane, 25 percent CO_2, contaminant-free, 50 mmbtu per day) and food grade liquid CO_2 (up to 1 ton per day). The PDU is located at the New Jersey Eco Complex, a new facility erected by the State of New Jersey at the Burlington County Resource Recovery Complex, Columbus, New Jersey. The complex includes a municipal sanitary landfill, recycling center, hazardous materials collection center, composting facility and a state-of-the-art, one-acre research and demonstration greenhouse. The project/status are discussed in Appendix E. The PDU process steps are:

- landfill gas compression to 400 psi and bulk water knock out;
- hydrogen sulfide removal with Sulfa Treat adsorbent;
- dehydration;
- contaminant removal by Acrion's CO_2 Wash™ technology;
- methane stripping from LCO_2 product;
- integrated CO_2 refrigeration system;
- LCO_2 product storage.

A blower system installed by the County can deliver up to 300 scfm landfill gas at about 40 inches water column. Acrion's PDU is designed to process about 100 scfm of LFG (about 900 gallons of LNG per day). To date, this is the largest operating system that Acrion has developed. The gas analysis reports do not confirm pipeline or LNG quality methane product. Therefore, a downstream gas clean-up technology must be incorporated. Other references contacted indicated that the system should be scaleable to LFG product stream criteria. No PDU system cost data were available. Exclusive rights to market the Acrion patented CO_2 Wash™ technology have been acquired by Firm Green Fuels of Irvine, California.

CONCLUSION

- **No commercial, small-scale LFG to LNG systems were discovered.**
- **Of the three most viable concepts, Acrion's technology appears to be nearest to commercial demonstration.**
- **No reliable cost data were discovered.**
- **Methane stripping from LFG at the purity required to produce LNG, is technologically difficult and system cost appears high.**
- **Markets for products (LNG, LCO_2, etc.) need to be near the production site.**
- **Minimum LNG production quantities for cost-competitive product are stated as 15,000 gallons per day.**
- **Current technology liquefaction production rates need to be greater than 1,000 gallons of LNG per day.**

TASK 2B.4 – ECONOMIC OVERVIEW

Nearly all landfills in the United States that collect LFG currently flare the collected gas. That is what SWACO does with the Franklin County Sanitary LFG. There is much interest in converting collected LFG into a useful, economically beneficial product. The major choices available in order of increased technical challenges and cost for use of LFG are:

- Direct use of LFG on site or in close proximity to the landfill. The primary direct use is for process heating.
- Electricity generation on site for on site usage and/or with direct sale to the local utility or other customers as a utility retail offset.
- Develop pipeline quality gas and sell it to the local gas company or national pipeline company.
- Convert the pipeline quality methane gas into compressed natural gas (CNG) for transportation fuel usage.
- Convert the methane into methanol for the chemical process industry.
- Convert the methane into LNG.
- Convert the LFG CO_2 into LCO_2.

Pipeline quality gas requires methane extraction from LFG and subsequent purification to meet pipeline quality criteria. The three most used processes to accomplish this objective are membrane separation, molecular sieve (pressure swing adsorption) and absorption process using a liquid solvent.

The technology status and known applications at this time are summarized below. On-site collection and flaring of LFG is by far the most common approach followed by on-site or near-site direct use of LFG for process heat and/or electricity generation. There are eight known projects that convert landfill gas to high-BTU (pipeline quality) gas in operation in the United States with three additional projects under construction and planned. All use membrane technology to obtain “clean methane.” No cost data were discovered.

There have been three LFG to CNG projects demonstrated worldwide. Los Angeles County, California, has successfully operated a CNG project at Puente Hills Landfill for nearly ten years. The demonstration project can produce 1,000 gge’s (gasoline gallon equivalent) per day. The gas is compressed to 3,500 psig and used to fuel several pieces of landfill equipment and Chrysler mini-vans. CNG usage is about 100 gge’s per day; thus the plant does not operate on a daily basis. The gas processed represents about 1 percent of collected LFG. Special, deep wells dedicated to this process were drilled to obtain as pure raw LFG as possible. The plant when built cost about $1,000,000 and uses membrane technology to remove CO_2 and contaminants. The processed LFG is 96 percent or greater methane, which is not pure enough to produce LNG. The owner states that they do not know the cost to produce a gge of CNG. Their purpose is not to prove cost-effectiveness, but to prove production and use technology. None of the LFG to CNG projects are of a commercial scale, thus no reliable cost information is available.

There are several known pilot LFG to LNG plants. One is at the Hartland Landfill in Victoria, British Columbus, Canada, and recently completed **initial performance testing**. A second is located in Burlington County, New Jersey. The Burlington County system was developed by Acrion Technologies and is based on an absorption process using a liquid solvent, LCO_2. The pilot system is to produce about 900 gallons of LNG per day. To date it has produced LNG for demonstration trials and at quantities below the target production point. Those involved consider the technology performs as expected and that the pilot system can be scaled to meet desired production quantities. The system design criteria are similar to those set for the Franklin County Sanitary Landfill Project. Firm Green Fuels of Irvine, California has procured exclusive rights to market the Acrion LFG to LNG technology. Additional **pilot** LFG to LNG projects **are planned** in California (2) and Texas (1). None of the known LFG to LNG processes or installations are of a commercial size. They are pilot/demonstration installations.

Conversion of LFG to methanol and ethanol for use as a vehicle fuel or as a chemical feedstock has been investigated in the United States since the early 1980s. There are no commercial scale LFG to methanol or ethanol projects known.

There are other known RD&D activities investigating many of these LFG opportunities. Previously in this report, the INEEL/Pacific Gas & Electric San Joaquin Valley project was discussed. Of interest is the GTI small-scale **liquefier development project** sponsored by the US DOE Brookhaven National Lab and GRI/GTI.

The working fluid is a patented, multi-component, mixed refrigerant. State-of-the-art HVAC screw compressor technology is used to ensure reliability and low compression costs. The system can be driven by an electric motor or a gas engine. Two systems have been built and tested. The first, **a lab prototype**, delivered 250 gallons per day of LNG from pipeline gas. The second, **a pre-commercial trial**, delivered 1,000 gallons per day of LNG from pipeline gas. A natural gas engine drive was utilized. The next step planned is to scale the design up to 5,000 to 10,000 gallons of LNG production per day from pipeline gas. **GTI is in ongoing discussions to seek a commercialization partner(s) before scaling the system to a commercial size.** They foresee the technology being applicable to production levels between 3,000 and 30,000 gallons per day of LNG. To date, the technical approach has been considered viable and the cost parameters as anticipated. The near-term methane feedstock for this technology is pipeline natural gas or remote natural gas reserves. Ultimately, LFG, wastewater gas and digester gas will be investigated. The **current target small-scale** (1,000 to 10,000 gallons of LNG per day) **capital cost** ($ per LNG gallon per day) is $400.

CONCLUSION

- **Direct use of LFG on site or in close proximity to the landfill can result in beneficial, economic use of LFG.**
- **Electricity generation for on site usage and/or direct sale to a local utility or other customers can result in beneficial, economic use of LFG. Target cost to sell the electricity is about 5 cents per kilowatt hour. A rule of thumb for electricity generation is 400 scfm of LFG at about 50 percent CH_4 content will generate 1 megawatt of electricity.**
- **Development and sale of pipeline quality methane gas can be a viable, beneficial, economic use of LFG. Membrane separation technology coupled with molecular sieve technology produces high Btu, high quality methane gas, which cost-effectively meets pipeline quality criteria. The pipeline must be located near proximity to the landfill.**
- **Producing CNG, LNG, LCO_2, methanol or ethanol at a commercial scale from LFG was not discovered. Therefore, no reliable cost data are available.**
- **It was stated, before the current price surges in the cost per barrel of oil, that LNG had to be made and sold for about 55 cents per gallon (without taxes) to meet**

customer purchase requirements. A major LNG producer in Texas indicated that the price point for a gallon of LNG was about 53 cents. FGF expects the price point for LNG per gallon at the Franklin County Landfill to be about 66 cents.

- **Combining several RD&D technologies may produce a more cost-effective system than use of a single technology.**
- **Additional demonstration projects would be helpful to the development of small-scale LFG to LNG technologies/systems. The Franklin County Landfill is a good candidate for a demonstration project.**

TASK 2B.5 – POST-PRODUCTION ON-SITE STORAGE, DISPENSING, AND TRANSPORTATION USE OF LFG TO LNG

Overview

Landfill gas (LFG), as previously stated, is predominantly a combined methane (CH_4) and carbon dioxide (CO_2) gaseous effluent resulting from the bio-degradation of landfill organic components and is normally collected and burned off ("flared") on-site, resulting in airborne releases of CO_2 and other pollutants. The promise of converting this waste product into liquefied natural gas (LNG) is in the availability of (relatively) low-cost, clean-burning, on-site LNG for powering internal combustion engines in various landfill-use related vehicles. LNG is an extremely clean-burning fuel with high energy density per unit volume or unit weight and has seen applications in refuse haulers and over-the-road Class 8 trucks typical in landfill-use. There is sufficient literature available to indicate that these engine/platform technologies have matured to the point of commercial marketplace availability from a number of competitive sources. Platforms are available from original equipment manufactures (OEMs) as new vehicles with LNG engines and LNG engines are available as retrofits into existing vehicles. However, vehicle use is only the end of the product trail. Between the final processing of LNG from LFG there must be installed either an on-site, cost-effective, safe, and reliable LNG storage and dispensing system or LNG must be imported from an off-site supplier and the landfill-use vehicles refueled on a timely basis directly from LNG tanker trucks.

On-Site LNG Storage/Dispensing

Storage requirements must take into consideration system maintenance requirements, system failure and/or other system down times, planned or otherwise. The following guidelines resulted from discussions with knowledgeable persons. It would be desirable to size storage equal to the volume of a tanker truck. This would suggest a volume of 12,000 to 15,000 gallons of LNG. For the Franklin County Landfill project, this volume would seem excessive when viewing LNG design production rate requirement of 1,175 gallons per day. A more reasonable approach would be to anticipate system down time and boil-off requirements that might approximate one week's usage of LNG. At the design production rate, that would suggest a storage capacity of 8,000 to 10,000 gallons of LNG.

Conversations with the one-time leading potential supplier of on-site LNG storage/dispensing packages indicated an estimated baseline equipment cost of $150,000 (varying grossly by design storage capacity) plus installation. Cost estimates were not current and did not include suggested operation and maintenance costs; potentially necessary redundancy and/or back-up system components' costs; local labor installation costs; or installation time estimates. Furthermore, this supplier had determined that there was a lack of a sufficiently sized LNG storage/dispensing package market and had basically abandoned further marketing of their system. Therefore, an engineered system consisting of a variety of components from numerous manufacturers would have to be designed, built, and installed in order to provide on-site packaged storage/dispensing of LNG for the landfill – greatly increasing infrastructure costs. Thus, the issue of on-site production of LNG from LFG, and on-site storage/dispensing of this LNG for landfill vehicle use becomes project specific and cost-effectiveness values deteriorate. If landfill vehicle emissions reduction was the only driver for this Project, imported LNG trailers dropped on-site can be suggested as a cost-effective near-term solution. However, large-scale LNG producers stated that trucking distances greater than 200 miles will result in uneconomical cost per gallon of delivered LNG. The desired trucking distance range for economical delivery of LNG is a 200 mile round-trip. The Franklin County Landfill is located approximately 350 miles from the nearest LNG production facility. Therefore, sufficient storage of LNG on-site is crucial to system (Project) economics.

<u>Landfill Use LNG Vehicles</u>
In the proposed Columbus OH landfill project, the user (SWACO) wished to initially purchase four new over-the-road Class 8 tractors to haul compacted waste from urban collection points to the landfill using LFG to LNG as an engine fuel. These units would replace four of SWACO's five oldest (1991-1992MY) units – specifically, International tractors powered by Cummins N4 375bhp diesel engines. By replacing four units per year, SWACO would eventually have a LNG- powered fleet of some 16-20 transfer trucks in operation. Given the current availability of natural gas-fueled heavy-duty engines in the 375 to 435 bhp range, and of LNG-ready Class 8 platforms, SWACO would be in a position to competitively bid their requirements from a number of sources. Appendix F summarizes the current SWACO fleet as of July 13, 2004. LNG-fueled Class 8 tractors for waste transfer duty can use suitable commercially-available platforms from a variety of manufacturers including: Mack/Volvo, PACCAR (Peterbuilt and Kenworth), and all of the other major domestic manufacturers. Any EPA-certified, natural gas-powered heavy-duty engine can operate on either liquefied or compressed natural gas – only the on-board fuel storage and delivery systems are different. Nominally, these engines are available from Cummins-Westport, John Deere, Mack, and Caterpillar. However, the existing SWACO newer vehicle fleet (1998-2004MY) horsepower requirements of 435bhp may limit the potential engine suppliers to Mack and Caterpillar. Natural gas-powered engines using modern electronic engine controls have advanced a great deal in reliability and serviceability over the last decade. However maintenance issues seem to be the biggest drawback in new applications and therefore service technician training, manufacturers' warranty support programs, fuel quality requirements, and other issues must be addressed by the user in the pre-bid process to help ensure cost-effective program implementation.

Costs for LNG-powered Class 8 trucks are higher than those for common diesel-powered vehicles, but lower than those for CNG-powered vehicles of similar horsepower, configuration, and powerplants due to the differential costs (and gross vehicle weight penalties) associated with on-board CNG fuel storage components. Currently, LNG-fueled vehicles of this type carry a cost premium of $35,000 to $50,000 over equivalent diesel units, while CNG-fueled HD vehicles carry a premium of $45,000 to $65,000. LNG-powered Class 8 trucks have similar vehicle weight and range as diesels, while CNG-powered trucks have a higher vehicle weight and less range due in part to the extra weight and supporting structure for on-board CNG storage tanks versus diesel or LNG tanks. Appendix F presents a comparison of diesel versus CNG versus LNG fuel tank size/weight. After the 2007 EPA regulations implementation for diesel engines in the 2007 to 2010 time period, the cost differential for a LNG engine versus a diesel engine may be reduced to the $10,000 to $30,000 range.

<u>Vehicular Emissions</u>
As an engine fuel, the use of LFG to LNG produced on-site, or LNG or CNG made available from other sources can provide significant emissions reduction benefits versus available diesel

and, when used in over-the-road vehicles should be recommended for CMAQ funding to cover the vehicles' incremental costs. In the waste transfer application proposed by SWACO, the high annual mileage should result in an acceptable annual cost-per-ton reduction in both oxides of nitrogen (NOx) and particulate matter (PM). In addition, some accounting can be made for the reduction of point source emissions by SWACO diverting significant quantities of otherwise flared landfill gas into LNG for use in clean vehicles.

TASK 2B.6 – PROJECT STATUS

Project implementation is dependent on FGF developing a market for the planned methanol production from the 1,554 million Btu per day of LFG that will be provided by SWACO. That market has not developed to date. A second consideration is the commercial status of the Acrion technology. The Burlington County, New Jersey project has similar design criteria to the planned Franklin County Landfill Project. The Acrion technology has not met the target design production rate or the methane quality rate desired without the use of other gas stream clean-up technology. Thus, the system has not reached a commercial development, production or economic state.

SWACO and COCFC are reviewing and considering other options for productive use of the Franklin County Landfill gas. No decisions as to uses and technologies have yet been made. SWACO appears to be waiting the conclusion of the FGF's Contract requirements before further evaluation of the Franklin County Landfill Gas Project.

CONCLUSION

- **The SWACO project, as discussed, is to provide methanol as a chemical feedstock and/or to produce a biodiesel fuel and to produce about 1,175 gallons per day of fuel grade LNG does not appear viable at this time. No buyer for the methanol has been identified and the Acrion technology is not commercially ready.**
- **LNG production at 1,175 gallons per day will not yield a cost effective product.**
- **The conversion of landfill gas to liquefied natural gas and the subsequent use of LNG in clean vehicles would be a public good. However, at this time, both technology-specific and overall cost-effectiveness, may be seen as problematic. The European Community has determined that shortening this process to the 'clean-as-necessary-for-combustion' quality and then using that processed gas to generate on-site electricity has become a viable and cost-effective near-term program.**
- **SWACO is committed to developing a viable LFG product that will be economically viable and yield environmental benefits. They are studying options with a strong desire to select projects for near-term implementation. Transportation fuels are definitely included in their desired options. The Franklin County Landfill and its owner SWACO are excellent candidates for a transportation fuels demonstration project.**

APPENDIX A

SUMMARY OF APPLICABLE LITERATURE

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APPENDIX B

- Franklin County Sanitary Landfill Gas Flare Data
- Summary of U.S. Landfills
- Miscellaneous Project Data

FRANKLIN COUNTY SANITARY LANDFILL
FLARE READINGS

		GEM Readings at Flare	Flare Reading	Calculated	
Date	Day	Methane	Flow	Flow	Notes
				MMBtu	
05-08-04	Sat				
05-09-04	Sun	61.3	2250	1,986.1	
05-10-04	Mon	59.5	2240	1,919.2	
05-11-04	Tues	59.8	2250	1,937.5	
05-12-04	Wed	58.7	2342	1,979.6	
05-13-04	Thurs	60.7	2351	2,055.0	
05-14-04	Fri	59.8	2357	2,029.7	
05-15-04	Sat	60.2	2317	2,008.6	
05-16-04	Sun	59.6	2210	1,896.7	
05-17-04	Mon	60.1	2340	2,025.1	
05-18-04	Tues	59.0	2330	1,979.6	
05-19-04	Wed	59.8	2445	2,105.4	
05-20-04	Thurs	59.9	2320	2,001.1	
05-21-04	Fri	59	2280	1,937.1	
05-22-04	Sat	59.3	2080	1,776.2	
05-23-04	Sun	60.8	2342	2,050.5	
05-24-04	Mon	59.9	2275	1,962.3	
05-25-04	Tues	60	2295	1,982.9	
05-26-04	Wed	60	2268	1,959.6	

FRANKLIN COUNTY SANITARY LANDFILL
FLARE READINGS

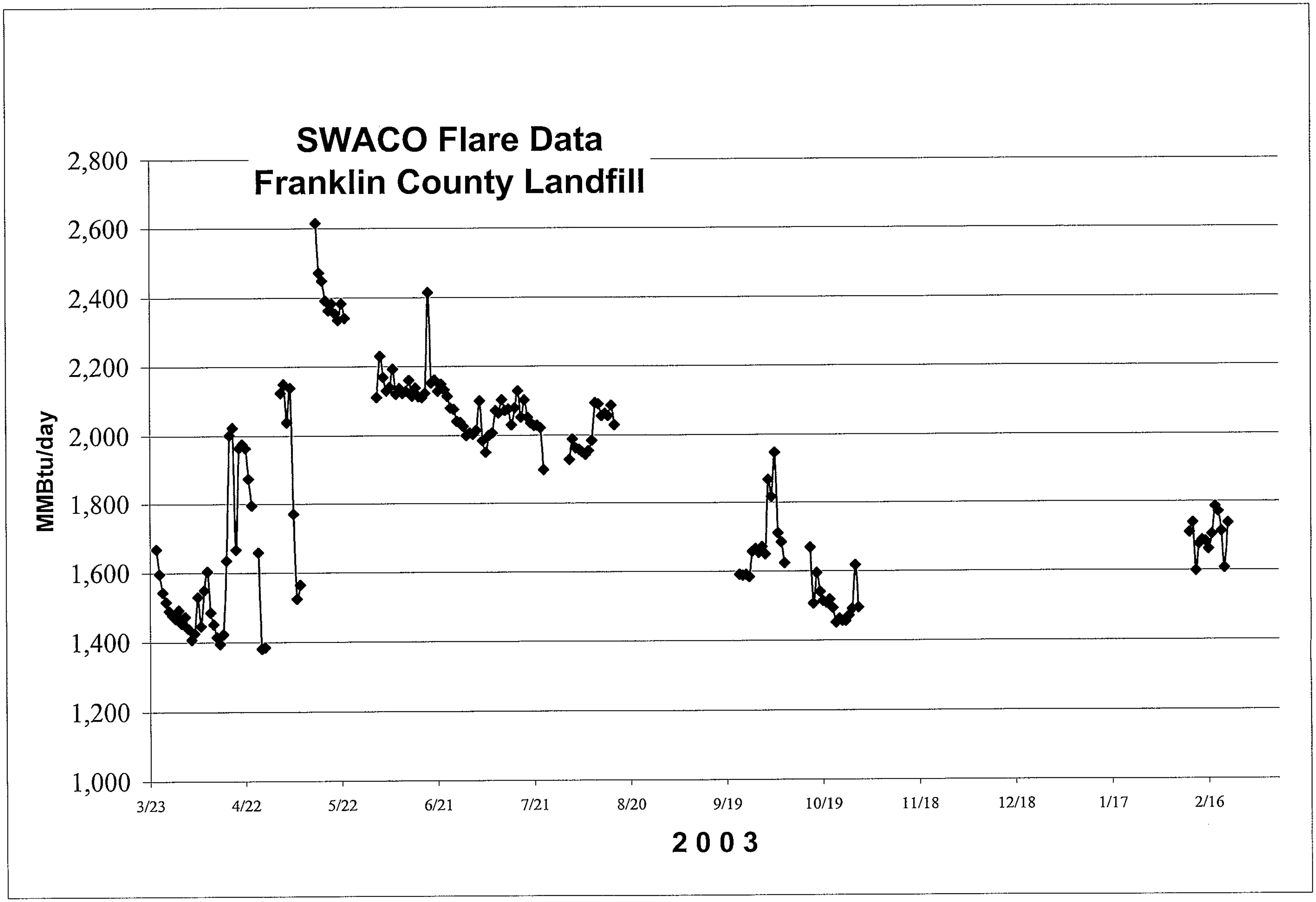
		GEM Readings at Flare	Flare Reading	Calculated	
Date	Day	Methane	Flow	Flow	Notes
				MMBtu	
05-27-04	Thurs	59.9	2150	1,854.5	
05-28-04	Fri	58.1	2200	1,840.6	
05-29-04	Sat	58.2	2320	1,944.3	
05-30-04	Sun	58.9	2310	1,959.2	
05-31-04	Mon	60.1	2330	2,016.5	
06-01-04	Tues	58.5	2310	1,945.9	
06-02-04	Wed	60.1	2300	1,990.5	
06-03-04	Thurs	57.8	2330	1,939.3	
06-04-04	Fri	58.6	2310	1,949.3	
06-05-04	Sat	57.5	2310	1,912.7	
06-06-04	Sun	59.1	2350	1,999.9	
06-07-04	Mon	58.7	2340	1,978.0	
06-08-04	Tues	56.9	2320	1,900.9	
06-09-04	Wed	57.4	2300	1,901.1	
06-10-04	Thurs	58.7	2290	1,935.7	
06-11-04	Fri	57.5	2290	1,896.1	
06-12-04	Sat	57.4	2300	1,901.1	
06-13-04	Sun	57.4	2320	1,917.6	
06-14-04	Mon	56.5	2320	1,887.6	

FRANKLIN COUNTY SANITARY LANDFILL
FLARE READINGS

		GEM Readings at Flare	Flare Reading	Calculated	
Date	Day	Methane	Flow	Flow	Notes
				MMBtu	
06-15-04	Tues	58.1	2310	1,932.6	
06-16-04	Wed	59.7	2340	2,011.7	
06-17-04	Thurs	60.4	2320	2,017.8	
06-18-04	Fri	61.2	2290	2,018.1	
06-19-04	Sat	61.8	2310	2,055.7	
06-20-04	Sun	63.9	2315	2,130.2	
06-21-04	Mon	61.1	2330	2,050.0	
06-22-04	Tues	60.6	2300	2,007.1	
06-23-04	Wed	59.6	2290	1,965.4	
06-24-04	Thurs	59.9	2280	1,966.6	
06-25-04	Fri	60.1	2300	1,990.5	
06-26-04	Sat	61.6	2350	2,084.5	
06-27-04	Sun	61.9	2340	2,085.8	
06-28-04	Mon	59.3	2300	1,964.0	
06-29-04	Tues	58.6	2330	1,966.1	
06-30-04	Wed	60.1	2340	2,025.1	
07-01-04	Thurs	56.1	2310	1,866.1	
07-02-04	Fri	56.4	2300	1,868.0	
07-03-04	Sat	58.7	2290	1,935.7	

FRANKLIN COUNTY SANITARY LANDFILL
FLARE READINGS

		GEM Readings at Flare	Flare Reading	Calculated	
Date	Day	Methane	Flow	Flow	Notes
				MMBtu	
07-04-04	Sun	58.1	2280	1,907.5	
07-05-04	Mon	57.9	2270	1,892.6	
07-06-04	Tues	57.3	2260	1,864.8	
07-07-04	Wed	58.0	2280	1,904.3	Last current 2004 reading.
07-08-04	Thurs			0.0	
07-09-04	Fri			0.0	
07-10-04	Sat			0.0	
07-11-04	Sun			0.0	
07-12-04	Mon			0.0	
07-13-04	Tues			0.0	
07-14-04	Wed			0.0	
07-15-04	Thurs			2,152.5	
07-16-04	Fri			2,161.2	
07-17-04	Sat			0.0	
07-18-04	Sun			0.0	
07-19-04	Mon			0.0	
07-20-04	Tues			0.0	
07-21-04	Wed			0.0	
07-22-04	Thurs			0.0	



SWACO Flare Data
Franklin County Landfill
MMBtu/day
2,800
2,600
2,400
2,200
2,000
1,800
1,600
1,400
1,200
1,000
3/23
4/22
5/22
6/21
7/21
8/20
9/19
10/19
11/18
12/18
1/17
2/16
2003

Landfill Name	Landfill City	Landfill County	WIP (tons)	Year Landfill Opened	Landfill Closure Year	Landfill Owner	Project Status	Project Start Date	Project Developer	Utilization Type (Direct-Use vs Electricity)	Specific Utilization Type	Capacity (MW)	LFG Flow to Project (mmscfd)	Emission Reductions (MMTCO2E)
Elda LF	Cincinnati	Hamilton	9,699,780	1971	1997	WMI	Operational	1/1/88	WMI	Direct	Direct Thermal		2.5	0.209
Rumpke SLF, Inc.	Cincinnati	Hamilton	11,500,000	1965	2004	Rumpke Sanitary Landfill, Inc.	Operational	1/1/86	GSF Energy	Direct	High Btu		8.4	0.702
American LF	Waynesburg	Stark	14,157,332	1975	2001	WMI	Potential			Direct			6.1	
Ashland County LF	Ashland	Ashland	1,099,797	1971	1997	Ashland County Commission	Unknown			Direct		0.80		
Athens-Hocking Reclamation Center	Nelsonville	Athens	1,056,530	1983	2009	Kilbarger Construction, Inc.	Unknown			Direct				
Bedford #1and #2 LFs	Columbus	Franklin	2,664,190	1975	1995		Operational	1/1/86	Network Energy	Direct	Boiler		2.0	0.167
BFI - Willowcreek LF	Atwater	Portage	16,141,779	1969	1992		Unknown			Direct				
Bigfoot Run SLF	Morrow	Warren	10,107,852	1970	1996	Allied Waste Industries	Potential			Direct				
Brown Brothers LF		Monroe		1970	1992		Unknown			Direct				
Brown County Landfill	Georgetown	Brown	1,500,000	1983	2006	Rumpke Waste, Inc.	Potential			Direct			0.6	
Buckeye Reclamation LF		Belmont			1991		Unknown			Direct				
Carbon Limestone LF	Lowellville	Mahoning	18,575,447	1969	2029	Allied Waste Industries	Operational	12/13/01	EDI	Electricity	Reciprocating Engine	14.85	8.0	0.529
Celina	Celina					Allied Waste Industries	Potential			Direct				
Cherokee Run LF/Laidlaw Waste Systems LF	Bellefontaine	Logan	6,000,000	1972	2012	Allied Waste (old LWS)	Operational	6/1/99	DTE Biomass	Direct	Leachate Evaporation		11.2	0.936
City of Brooklyn LF	Brooklyn	Cuyahoga			2006		Unknown			Direct				
City of East Liverpool LF	East Liverpool	Columbiana	1,037,357	1960	2012	East Liverpool LF, Inc.	Unknown			Direct				
City of St. Marys LF	St. Marys	Auglaize	1,142,214	1965	1998	City of Saint Marys Refuse Department	Unknown			Direct				
City Westlake LF		Cuyahoga	235,750	1968	1990		Unknown			Direct				
City Xenia LF		Greene	430,008	1968	1990		Unknown			Direct				
Cleveland Land Development LF	Brooklyn Heights	Cuyahoga	2,985,302	1970	1995		Unknown			Direct				
Countywide Recycling & Disposal LF	East Sparta	Stark	8,238,436	1968	1997	WMI	Potential			Direct				
Crawford County Sanitary LF	Bucyrus	Crawford	1,562,265	1969	2011	Crawford County Board of Commissioners	Unknown			Direct				
Crossridge LF		Jefferson	596,840	1984	1991		Unknown			Direct				
Cuyahoga Regional Sanitary LF	Solon	Cuyahoga	10,000,000	1972	1996	WMI	Operational	1/1/99	NEO	Electricity	Reciprocating Engine	3.50	1.5	0.125
Cuyahoga Regional Sanitary LF	Solon	Cuyahoga	10,000,000	1972	1996	WMI	Operational	1/1/01	EMCON/OWT and NEO	Direct	Boiler	3.80	0.4	0.033
Defiance County LF	Defiance	Defiance	2,548,679	1971	2001		Unknown			Direct				
Doherty LF	Geneva	Ashtabula	1,462,491	1978	2008	Doherty Sanitary LF, Inc.	Unknown			Direct				
Erie County SLF	Huron	Erie	2,920,000	1969	2040	Erie County	Potential			Direct				
Evergreen Recycling & Disposal LF	Northwood	Wood	6,000,000	1973	2013	WMI	Operational	1/1/99	Toro Energy	Direct	Boiler		1.1	0.092
Evergreen Recycling & Disposal LF	Northwood	Wood	6,000,000	1973	2013	WMI	Operational	9/1/01	Toro Energy	Direct	Direct Thermal		2.2	0.184
Fairfield Sanitary LF	Amanda	Fairfield	3,014,323	1981		WMI	Unknown			Direct				
Fowler LF	Fowler Township	Trumbull	5,167,297	1960	1990		Unknown			Direct				
Franklin County SLF	Grove City	Franklin	7,000,000	1985	2030	Solid Waste Authority of Central Ohio	Potential			Direct				
Gallia County LF	Bidwell	Gallia				Gallia County Commissioners	Unknown			Direct				
Glenwillow Sanitary LF	Solon	Cuyahoga	6,408,560	1965		Allied Waste Industries	Potential			Electricity		2.70	1.5	

Hancock County Sanitary LF	Findlay	Hancock	2,450,000	1969	2065	Hancock County Commissioners	Potential			Direct				
Hardin County LF		Hardin			1990		Unknown			Direct				
Hardy Road LF	Akron	Summit	6,014,112	1969	2001	City of Akron	Operational	11/1/01	Granger Energy	Direct	Direct Thermal	1.60	0.8	0.067
Henry County LF	Malinta	Henry	956,918	1968		Henry County Commissioners	Unknown			Direct				
Hoffman Road Sanitary LF	Toledo	Lucas	5,416,000	1974	2004	City of Toledo	Construction		U.S. Energy Biogas Corp.	Direct	Direct Thermal		2.7	0.229
Holmes County LF	Millersburg	Holmes	648,641	1971		Holmes County Commissioners	Unknown			Direct				
Huron County LF	Willard	Huron	1,464,341	1969	2008	Huron County Commissioners	Unknown			Direct				
Kimble Sanitary LF	Dover	Tuscarawas	6,611,084	1976	2027	Kimble Clay & Limestone Company	Unknown			Electricity				
Lake County LF	Painesville	Lake	1,000,000		2006	Lake County DPW	Operational	10/1/99	Granger Energy	Direct	Boiler		1.4	0.120
Lake County Solid Waste LF	Painesville	Lake	6,182,088	1973	2006	Lake County	Potential			Direct				
LF	Twinsburg						Unknown			Direct				
LF	Findlay						Unknown			Direct				
LF	Springfield						Unknown			Direct				
Lorain County I/II LF	Oberlin	Lorain	12,529,697	1974	2000	Allied Waste Industries	Operational	12/3/01	EDI	Electricity	Reciprocating Engine	8.10	4.5	0.289
Middletown City LF	Middletown	Butler	2,800,000	1963	1990	City of Middletown	Unknown			Direct				
Miller City LF		Putnam		1969	1991		Unknown			Direct				
Model Landfill	Grove City	Franklin		1967	1985	SWACO	Operational	5/1/01	EDI	Electricity	Reciprocating Engine	4.05	1.8	0.144
Montgomery County LF	Dayton	Montgomery				Montgomery County Board of Commissioners	Unknown			Direct				
Mt. Eaton East LF	Mt. Eaton	Wayne	4,544,358	1969	1998	Wayne County	Unknown			Direct				
Nicky Boulevard LF		Cuyahoga		1968	1990		Unknown			Direct				
Ottawa County LF	Port Clinton	Ottawa	6,032,659	1970	2002	Allied Waste Industries	Operational	4/1/01	EDI	Electricity	Reciprocating Engine	2.60	1.5	0.093
Pike Sanitation LF	Waverly	Pike				Pike Sanitation Company	Unknown			Direct				
Pinnacle Road LF	Dayton	Montgomery	1,000,000			WMI	Construction		DTE Biomass	Direct	High Btu		0.8	0.067
Preble County LF	Eaton	Preble				Preble County Commissioners	Unknown			Direct				
Putnam County LF	Ottawa	Putnam	531,308	1969		Putnam County Commissioners	Unknown			Direct				
Reserve Environmental Services LF							Unknown			Direct				
Rossford LF		Wood	104,814	1964	1990		Unknown			Direct				
Royalton Road Sanitary LF	Broadview Heights	Cuyahoga	5,627,995	1969	2030	Norton Environmental Company	Unknown			Direct				
Scioto Sanitation LF		Scioto	347,907	1969	1989		Unknown			Direct				
State Wide LF	Canton	Stark	1,000,000		1990	WMI	Operational	1/1/99	Toro Energy	Direct	Medium Btu		0.7	0.060
Stony Hollow LF	Dayton	Montgomery	1,500,000			WMI	Construction			Direct	High Btu		1.3	0.109
Tremont LF	Springfield	Clark	4,720,924	1969	1995	Davis	Construction		Springfield Gas/Custer Services	Direct	Boiler		2.0	0.170
Triangle LF	South Salem	Ross	1,332,511	1974	1993	Triangle Landfill, Inc.	Unknown			Direct				
Village Cedarville LF		Greene			1990		Unknown			Direct				
Williams County LF	Bryan	Williams	4,973,752	1969	1997	Allied Waste	Potential			Direct				
Wood County Landfill	Bowling Green	Wood	858,259	1972	2014	Wood County Solid Waste District	Potential			Electricity		0.03		
Wyandot Sanitary LF	Carey	Wyandot	3,700,000	1968	2033	American Disposal	Potential			Electricity		2.00		

Bob Brown
216 573 1187

8/6/10/04

Acrion Techny - 10/30 spoke w/ Marina Neyman. Very interested in project. Connected to IFC & Mack. Part of Rutgers LFG-FC study (Acrion is best techny), which included greenhouse & educational aspect. Will be in NJ for project Nov 5-8.

Braintree - $1.5 million project ($200k DOE, $100k MA Div Energy Resources) began in Sept 1999 with IFC. High nitrogen levels resulted in combining natural gas with LFG at new fuel blending station, then go into FC to create electricity which will be directly fed to city's power grid. (see contacts)

Braintree Elect Light Dept (MA) 781.348.1010 - Walter McGrath - msg 10/30. Joe who? 781.348.1070
Nov 6 ANSI

Installed 200kw IFC/~~Awnse~~ Phosphoric Acid fuel cell in Sept 1999. Unit has only operated about 4 months total due to high Nitrogen levels (tests did not show problem, phenomenom seems to creep up after few months). Believe landfill was not capped properly, spent $100k in 2001 to repair caps (air leaking in). Original plan to add natural gas blending unit, to suppliment LFG over time as amounts likely decreased. But added unit now, will likely add blend to "lower" amount of nitrogen. Are also going to check individual wells for nitrogen levels, turning off those with higher levels. IFC has good website on product, of 200-300 FC's on market, 98% are running on natural gas, ~2% on LFG or other. Joe feels FCs best in places valuing secure supply of electricity over costs (~2week cleaning downtime/year). Phosphoric Acid FC is 35-40% efficient w/o utilizing hot water excess, 80% with. Braintree ran piping over to nearby hotel to possibly share/use hotwater in future, but not until project levels. Project began due to Board interest in pursuing. Joe's advice, "know your dump - what is in it, levels of LFG". FC's about $700k and cleaning units up to $200k.

Rutgers Univ, NJ EcoComplex - 609.499.3600 ext 226 - David Specca, Dir Developmental Programs 10/31. Using Acrion system to clean LFG, then using it to heat research Greenhouse (since 96) and fuel boiler (since 2000). Cleaning 130cubic feet/minute. Looking at using FC, likely go with Molton Carbonate (CO2 of LFG helps) or Solid Oxide. However, former costs $2M. Phosphoric Acid FC have difficulty with Nitrogen levels in LFG, changes pH balance. Weak leak in LFG>FC is in cleaning gas, costly. Believes vehicle fuel is most economical use of LFG, powering FC is second. Recommends using equipment that has (make sure!) been used in other locations. Talk to Mack Truck, who are very interested in capturing LFG for vehicles.

FuelCell Energy - 203.825-6122 - George Steinfeld, Landfill Gas Prog Mgr. No active LF projects now, but have tested perviously. Now focus on natural gas powered Carbonated FC. 250kw, 1mw & 2 mw. Are in Field Demonstration/trails with product. Mentioned big contamenant is chlorine, and some sulpher. Cost of Electricity is 1/3 fuel, 1/3 capital, and 1/3 operating & maintenance costs. Has Coalmine Methane FC project in Katies, OH - 90 miles west of Pittsburgh. EPRI studies include TR-100050 - 1991- Evaluation of 2mw FC powered by LFG and TR-108043-VI - 1997-design and testing of facility run by carbonated FC.

Nov 7 Rich Shaw (rshaw@fce.com) & Steinfeld, conf call - very interested in project, need to know more about trace elements in LFG but feel current "pipeline quality" is good sign. Are in "Field Trial" operations - with ten in new operation. LA DWP is operating 250kw. Planned for Minn landfill demo, funding fell thru, so only tested on LFG quality fuel, not actual in use demo. Using Molten

Carbonate FC. Is 50% efficient, better with cogen. 10-12 cents/kwh total costs, 12-14 w/o funding assistance (net over equipment cost). Footprint is 290 sq ft for the 250kw unit. Also interested in avoided cost of electricity. www.fce.com

Allied Waste (BFI) - Doug Burrow 480.627.2700 [EK Cinci spoke with Rob Dolder, who suggested contacting Scottsdale, AZ corp office, as he cannot make that decision. Site is trying to expand and having difficulty with community] --- msg **Nov 13**, out of office. Secty provided name of Doug Junk (Younk) [480.627.7079] who works on LFG projects. Apparently they already do this and sell it.

Metro Sewer - Tom Schweir 513.577.7108 or Cassandra (assistant) 513.244.1351
Dan Fitcher of EK has worked with Metro Sewer.

Gail Cassellos, MASS DEP Rideshare program 617.338.2255
Nov 15 - have Rideshare program for businesses. Must report drive alone trips and reduce them as requested (say by 25%). Program has goals and accepted Alternative Mitigation Measures, of which carsharing is one option (along with providing transit passes etc). Also can use carshare as part of Guaranteed ride home program.

<u>Other Projects:</u>
Groton's Flanders Road Landfill - using phosperic acid FC to convert LFG to electricity at 42 acre site. 165 kw (1.6 million kw/hrs) output, recovering more than 80% of LFG's energy value. Partnership between Groton, CT Light & Power, IFC and EPA. Cost $1-1.5 million.

Tremont City landfill - with partner Springfield Gas Co., Inc., site will use LFG as fuel for boilers and other plant units. Project has taken years to evolve, but expects to be in operation in 2002. Strong community opposition, countered by strong outreach and PR campaign, delayed actions.

LA County Sanitation District - owns and operates countries only compressed biogas facility in US. has operated since 1995 at a capacity of 1,000 gge/day. Fuel production costs range from 40 to 85 cents per gge. Using gas to fuel vehicles??

AT&T Columbus Ohio - 1992 - Gahanna landfill piping gas thru 1.5 mile pipe to AT&Ts 50 acre facility to be used as boiler fuel. Estimated to save over $60,000/year and last 30 years.

EK Cinci - Mohamad Musa has worked in methane recovery, is interested in project!

APPENDIX C

LNG Conversion Factors

LNG Conversion Factors

LNG

Item	1 Metric Tonne	1 Barrel	1 Gallon	1 Cubic Meter	1 Cubic Foot	1 Pound
1 metric tonne - LNG	1	14.04	589.67	2.232	78.827	2,204.6
1 barrel - LNG	0.0712	1	42	0.159	5.615	157.1
1 gallon - LNG	0.001696	0.0238	1	0.00379	0.1337	3.7
1 cubic meter - LNG	0.448	6.290	264.172	1	35.315	988.0
1 cubic foot - LNG	0.0127	0.178	7.482	0.0283	1	28.0
1 cubic meter - Gas	0.000734	0.0103	0.433	0.00164	0.0579	1.6
1 cubic foot - Gas	0.00002	0.0003	0.012	0.00005	0.0016	0.046
1 Mcf - Gas	0.0208	0.292	12.266	0.0464	1.640	46.0
1 MMBtu - Gas	0.0193	0.272	11.402	0.0432	1.524	42.7

Reference: Gas Technology Institute

Business Development Group, Inc.

17 JAN 05

To: A. J. Parker, Jr., P.E.
Edwards and Kelcey
Tel 410-646-4505
Fax 410-646-4557
E-mail: AParker@EKmail.com

From: M. L. Pomerantz
Tel 412-882-0184
Fax 412-882-0185
E-mail: pomerantzm@asme.org

Subj. Liquid Methane Production

Dear Andrew:

The purpose of this memo is to modify my previous opinion about the production of liquid methane. On 12 JAN 05 Ed Vogel, David Wentworth, and I, visited the Acrion facility at the New Jersey EcoComplex. Bill Brown gave us a detailed tour including a description of the refueling operation. He also gave me information about the properties of liquid methane. Based on this information I want to change my recommendation about the estimates of liquid methane production and the diesel fuel equivalence calculation.

First I want to repeat the references I quoted in my earlier e-mail.

1. *North American Combustion Handbook*, Vol. I, Third Edition
<u>Methane Properties</u>
Gross heating value (Higher Heating Value - HHV)
    1,012 Btu/scf and 23,875 Btu/lb
Net heating value (Lower Heating Value - LHV)
    911 Btu/scf and 21,495 Btu/lb
<u>Fuel Oil Properties- #2 Distillate Oil</u>
Gross heating value (Higher Heating Value - HHV)
    137,080 Btu/gal and 18,993 Btu/lb
Net heating value (Lower Heating Value - LHV)
    128,869 Btu/gal and 17,855 Btu/lb

2. *A Comparison of LNG, CNG, and Diesel Transit Bus Economics*, Gas Research Institute Topical Report, October 1993.
    Diesel fuel: 128,100 Btu/gal (LHV)
    LNG: 77,500 Btu/gal (LHV)
    Natural gas: 930 Btu/scf (LHV)

Vehicle fuels are compared by LHV values. Boilers and barbecues use HHV because this is how natural gas is sold. The CNG LHV of 930 Btu/scf is the mean value for the United States and it can vary depending upon the location. The LNG LHV of 77,500 Btu/gal is for a typical natural gas stored as a saturated liquid at about 20 psig. This is higher than pure methane saturated liquid at 20 psig.

3. Another reference had:
   Diesel fuel at 18,300 Btu/lb and 128,100 Btu/gal
   Liquid methane at 21,500 Btu/lb and 77,400 Btu/gal

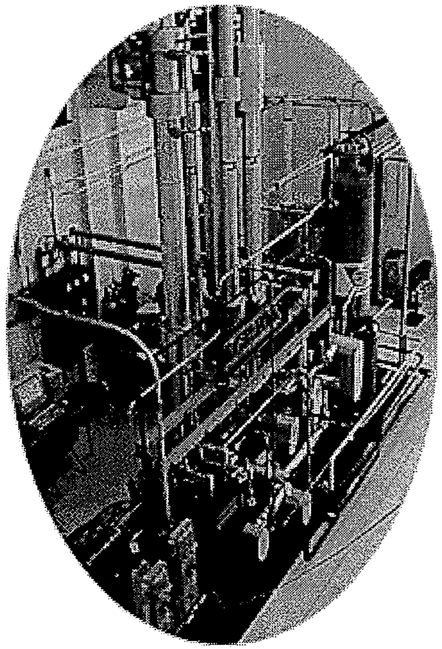
No statement was made with regard to LHV.

APPENDIX D

Renewable Fuels and CO_2
Acrion Technologies, Inc.

Acrion Technologies, Inc.

Renewable Fuels and CO_2

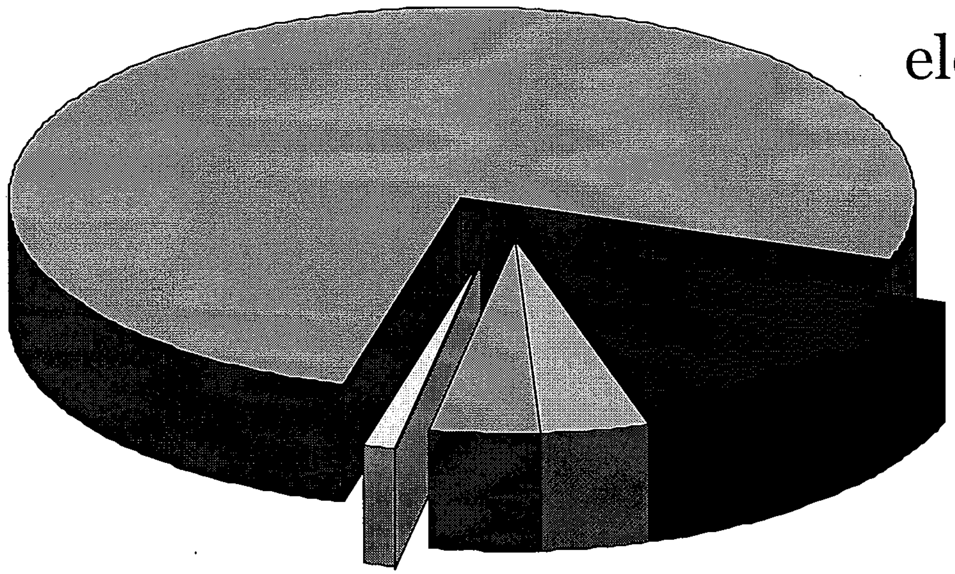


Award R&D 100 Winner

Acrion Technologies

LFG Utilization

204 sites



Acrion
Technologies

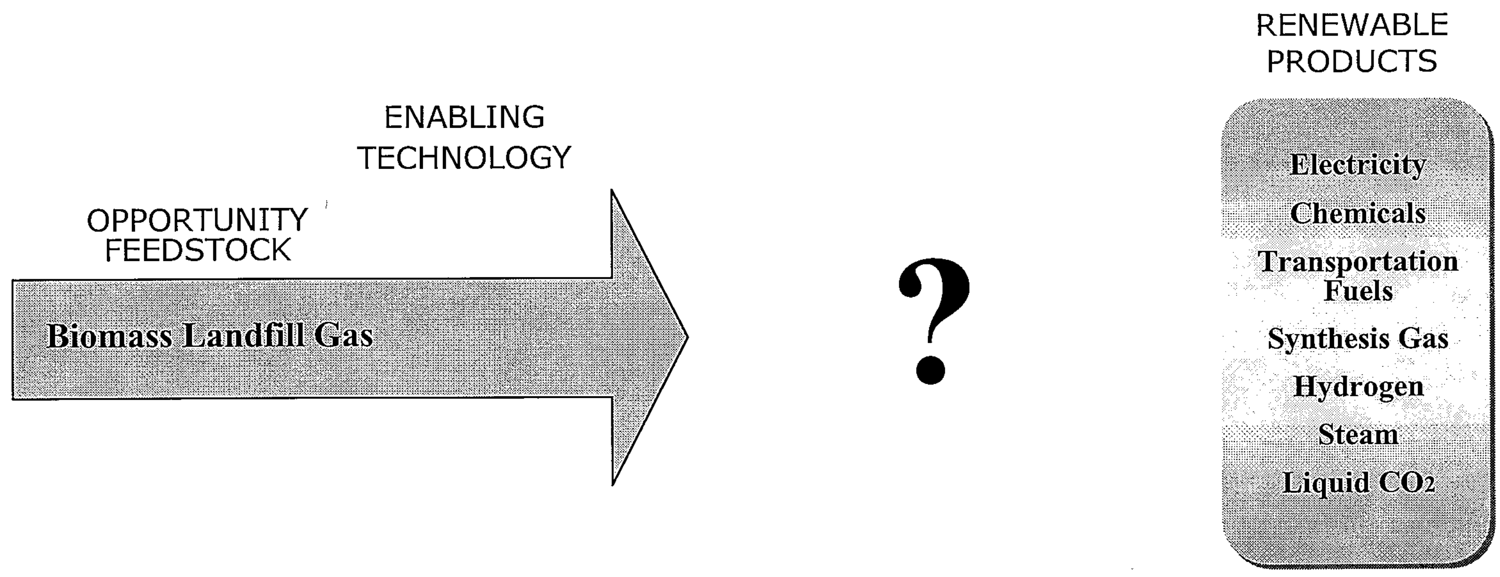
CO_2 Wash™
Enabling Technology

OPPORTUNITY
FEEDSTOCK

Biomass Landfill Gas

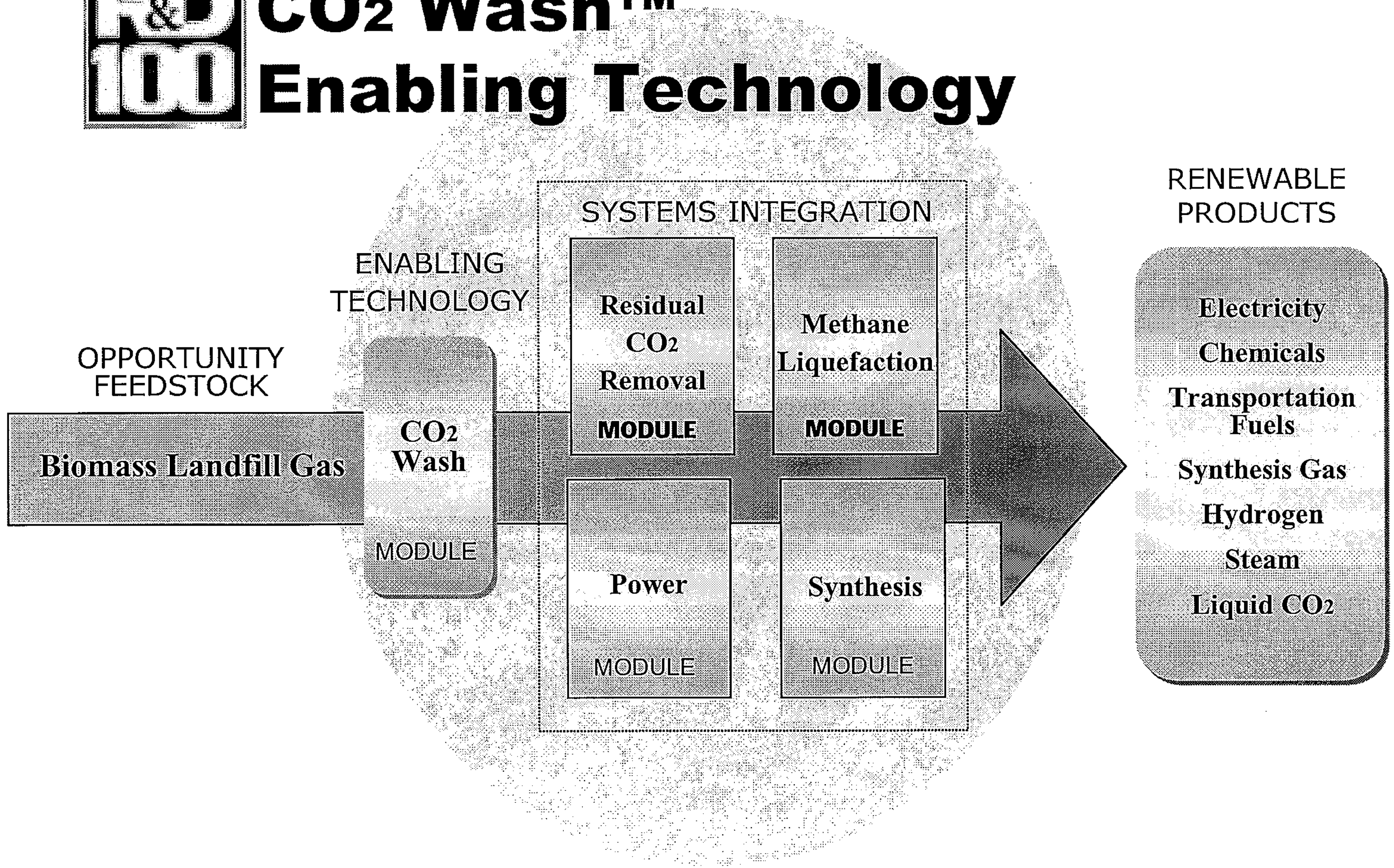
Acrion Technologies

CO_2 Wash™ Enabling Technology



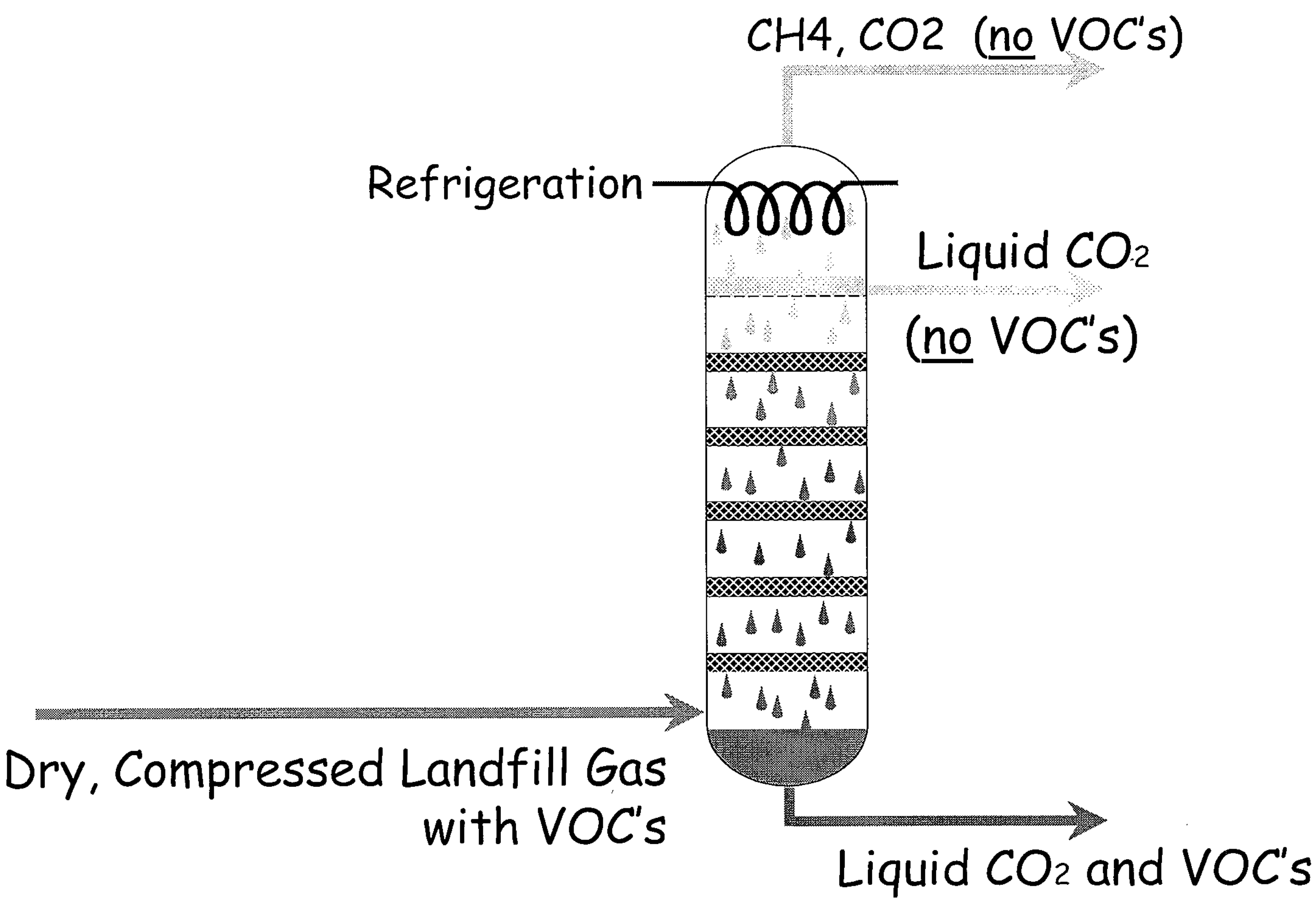
Acrion Technologies

CO_2 Wash™ Enabling Technology



Acrion Technologies

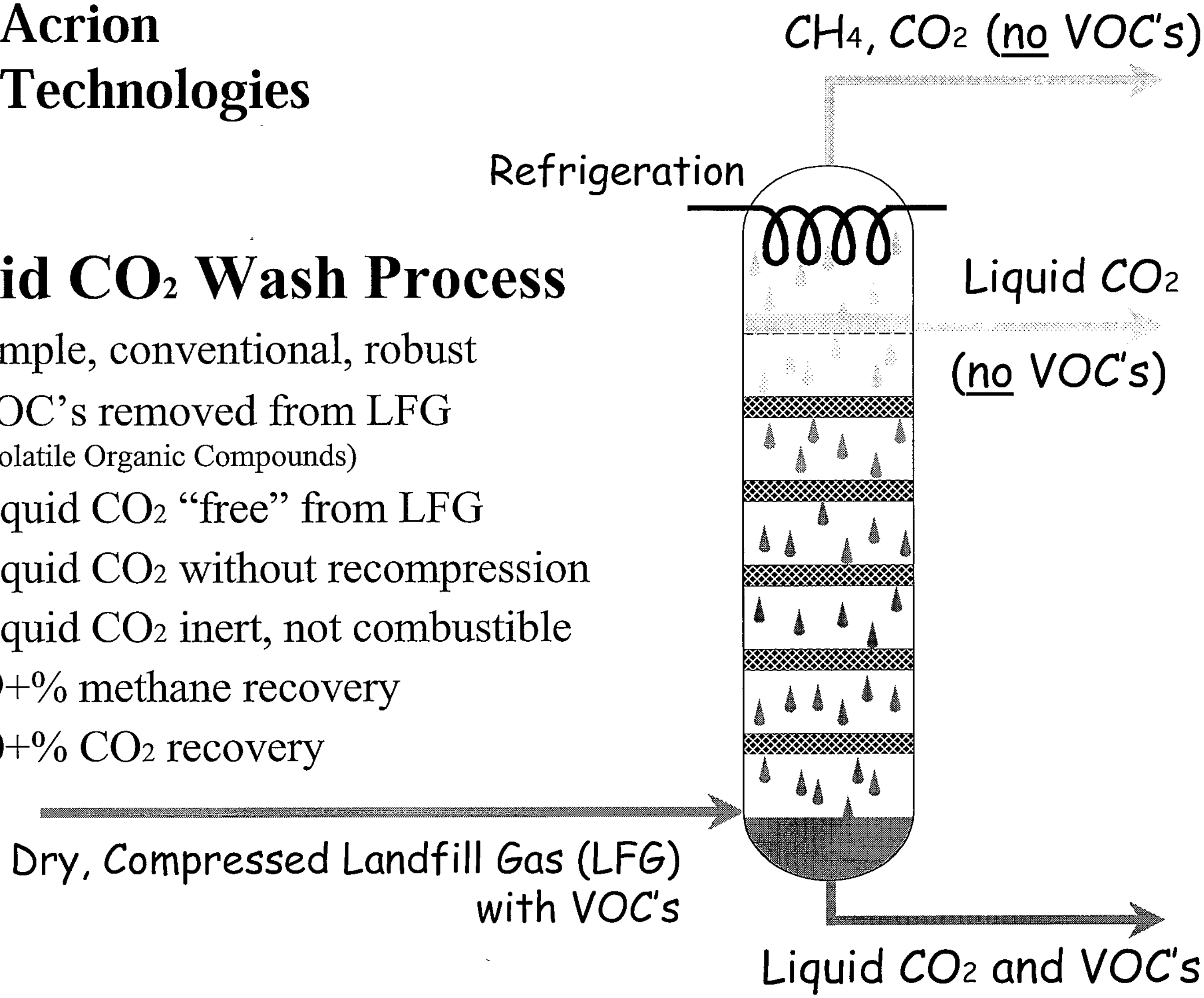
CO_2 Wash Process



Acrion Technologies

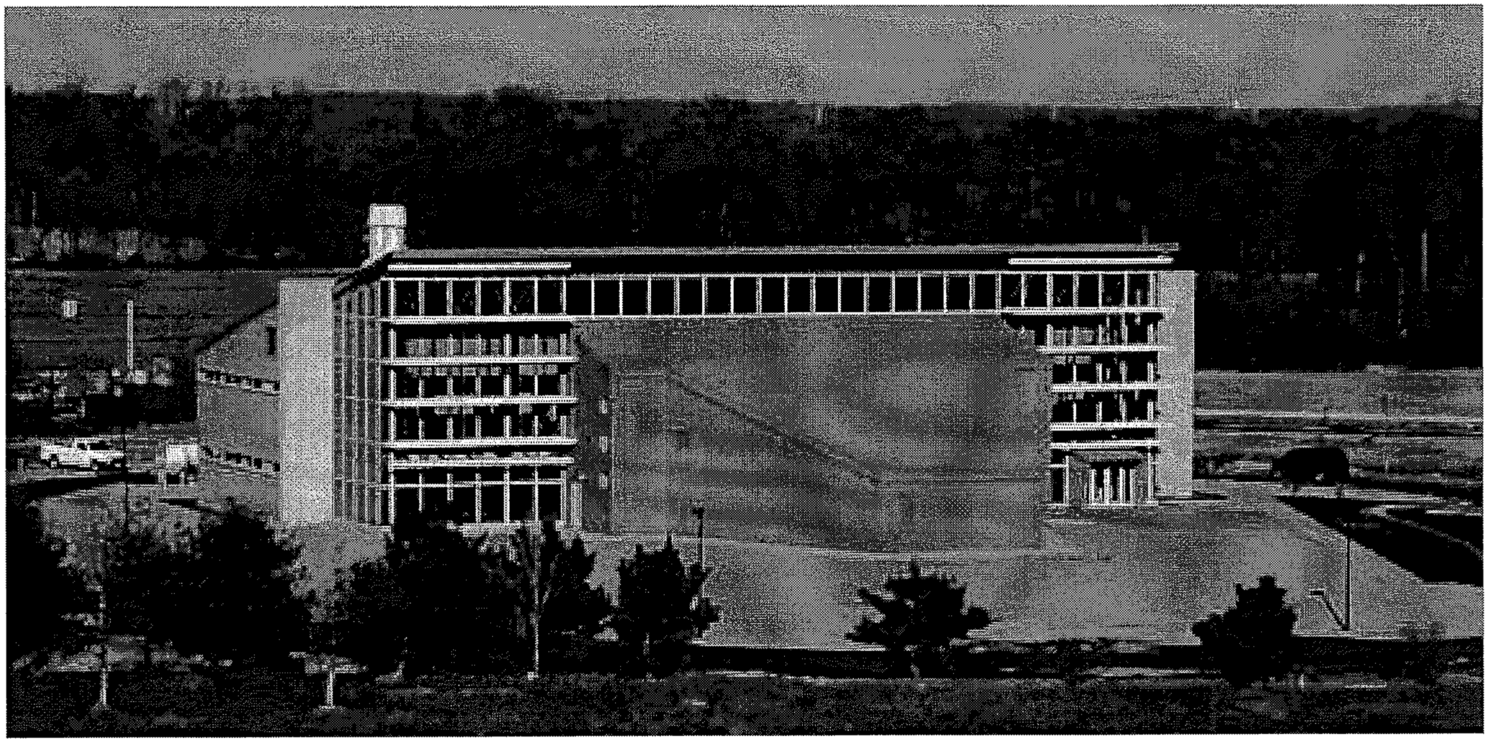
Liquid CO_2 Wash Process

- Simple, conventional, robust
- VOC's removed from LFG (Volatile Organic Compounds)
- Liquid CO_2 "free" from LFG
- Liquid CO_2 without recompression
- Liquid CO_2 inert, not combustible
- 99+% methane recovery
- 80+% CO_2 recovery



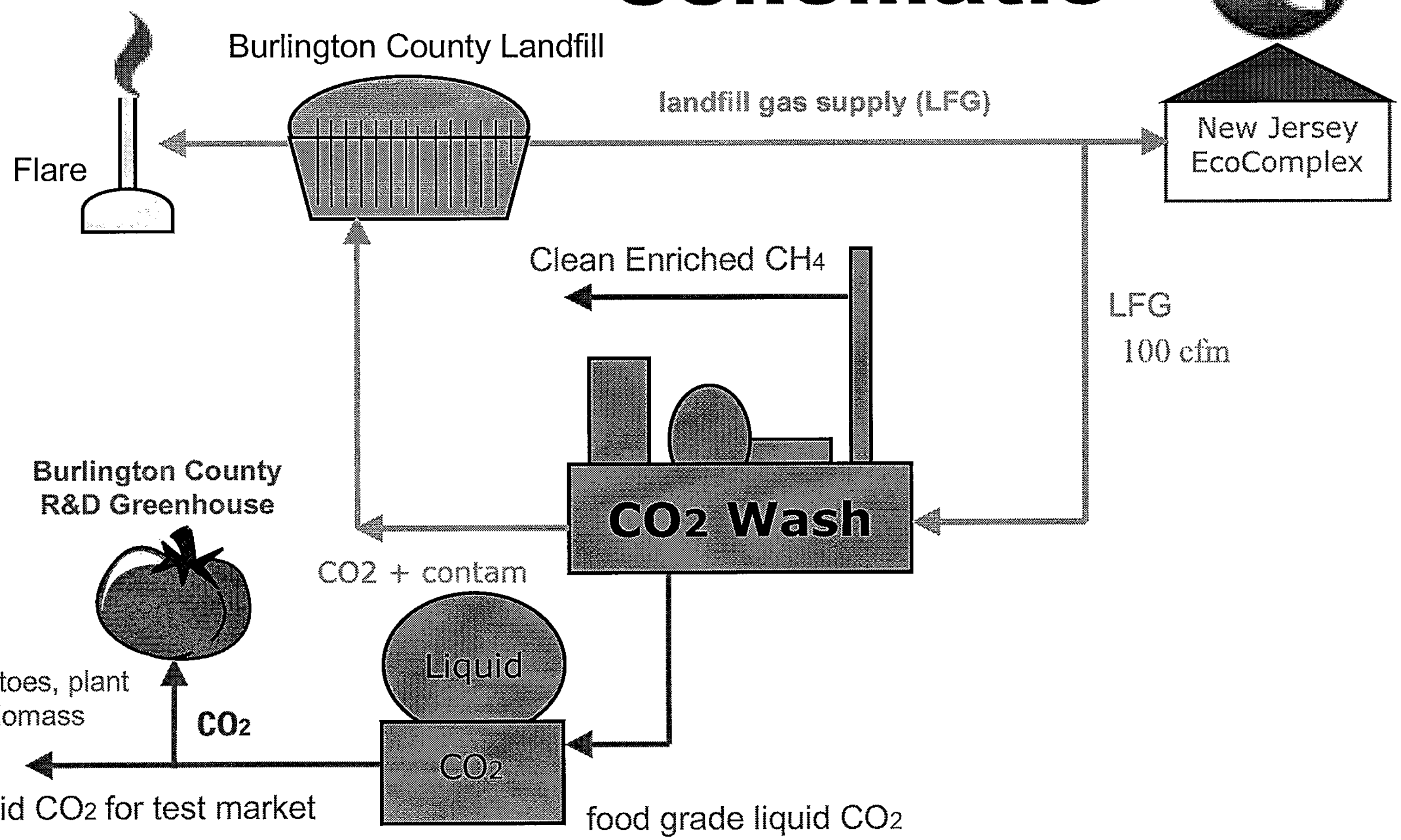
Acrion
Technologies

New Jersey EcoComplex



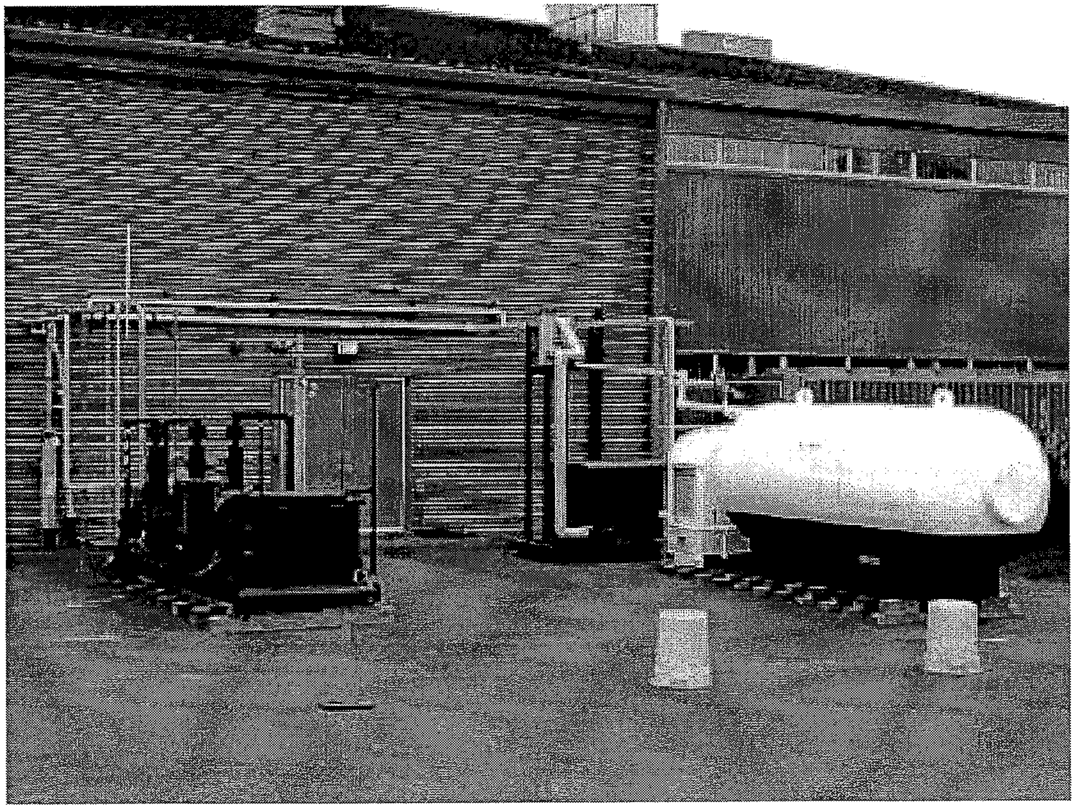
Acrion Technologies

PDU Schematic



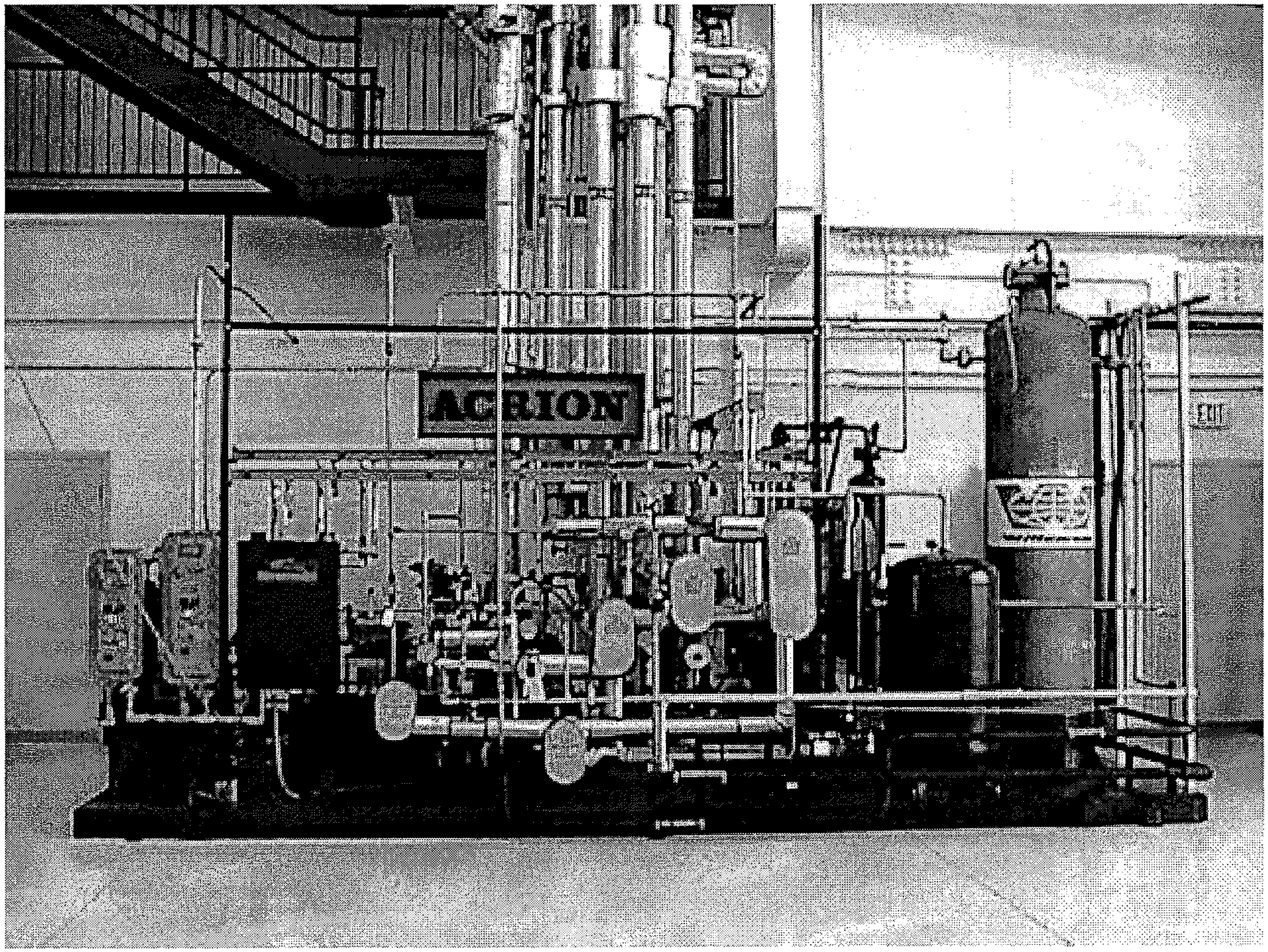
Acrion
Technologies

CO_2 Wash Aux Equipment



Acrion
Technologies

CO_2 Wash Skid



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Technologies

Quality Products!!

- Methane Product: < 100 ppb VOC
- Siloxanes: ND at 5 ppb
- Liquid CO_2: > 0.9999

Acrion
Technologies

ppm Siloxane - so what?

- Burlington County LFG
- 2.65 ppm Siloxane
- 2,000 scfm Engine Fuel
- 2 kg Sand (SiO_2) / day

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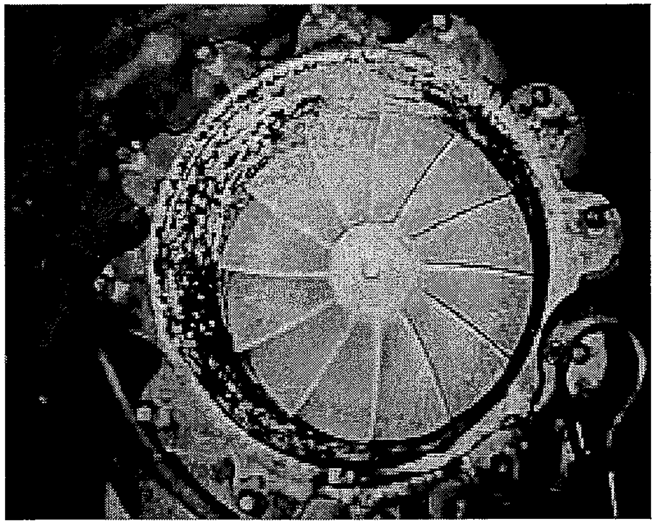
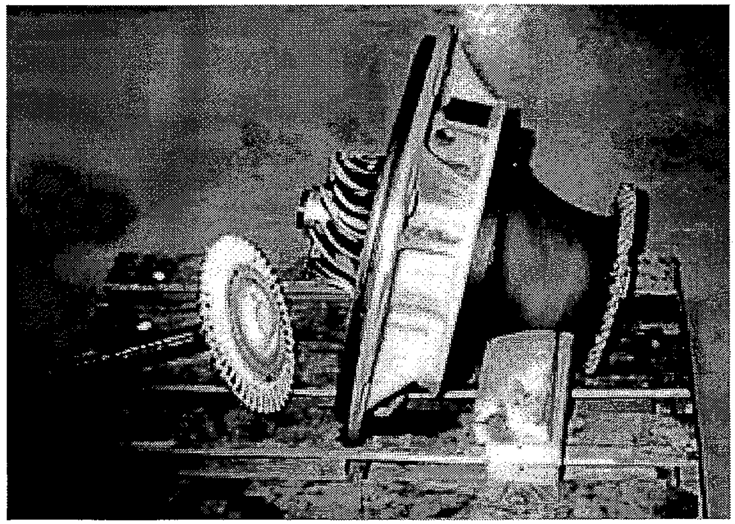
Technologies

These Aren't Bank Deposits





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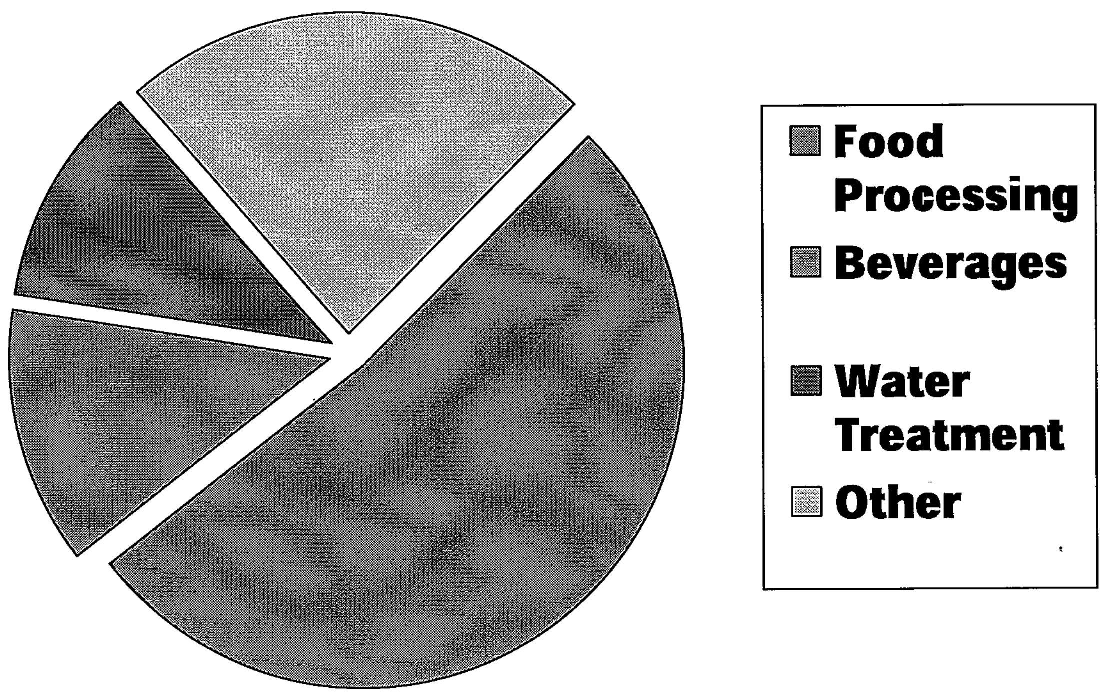
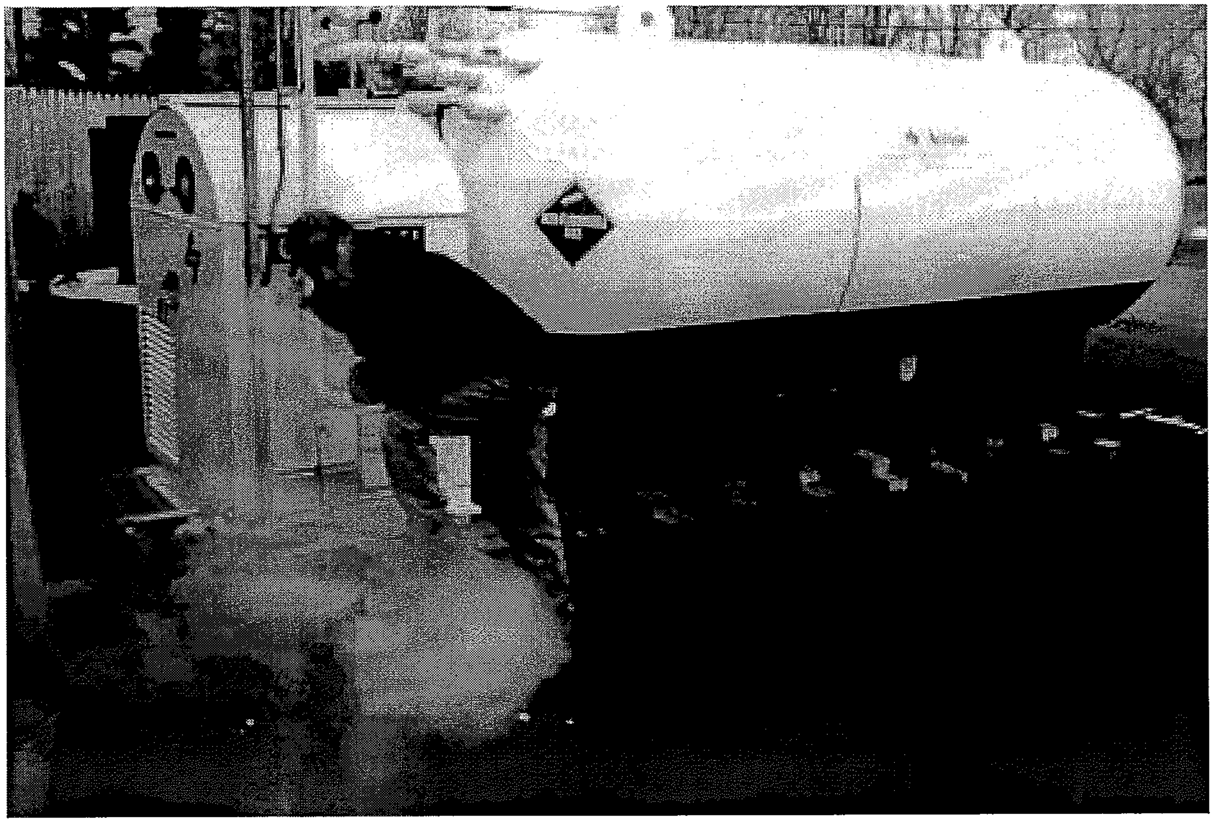
Technologies

Liquid Carbon Dioxide



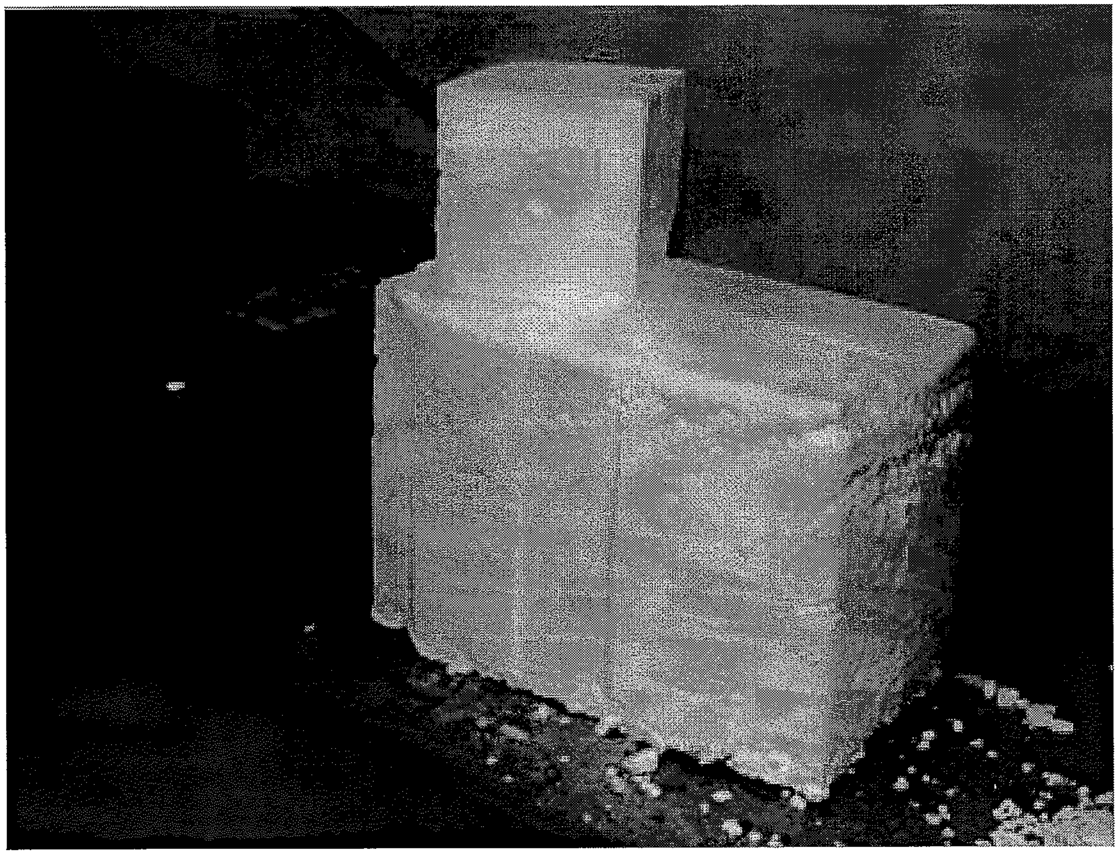
Acrion
Technologies

Sparkling LFG



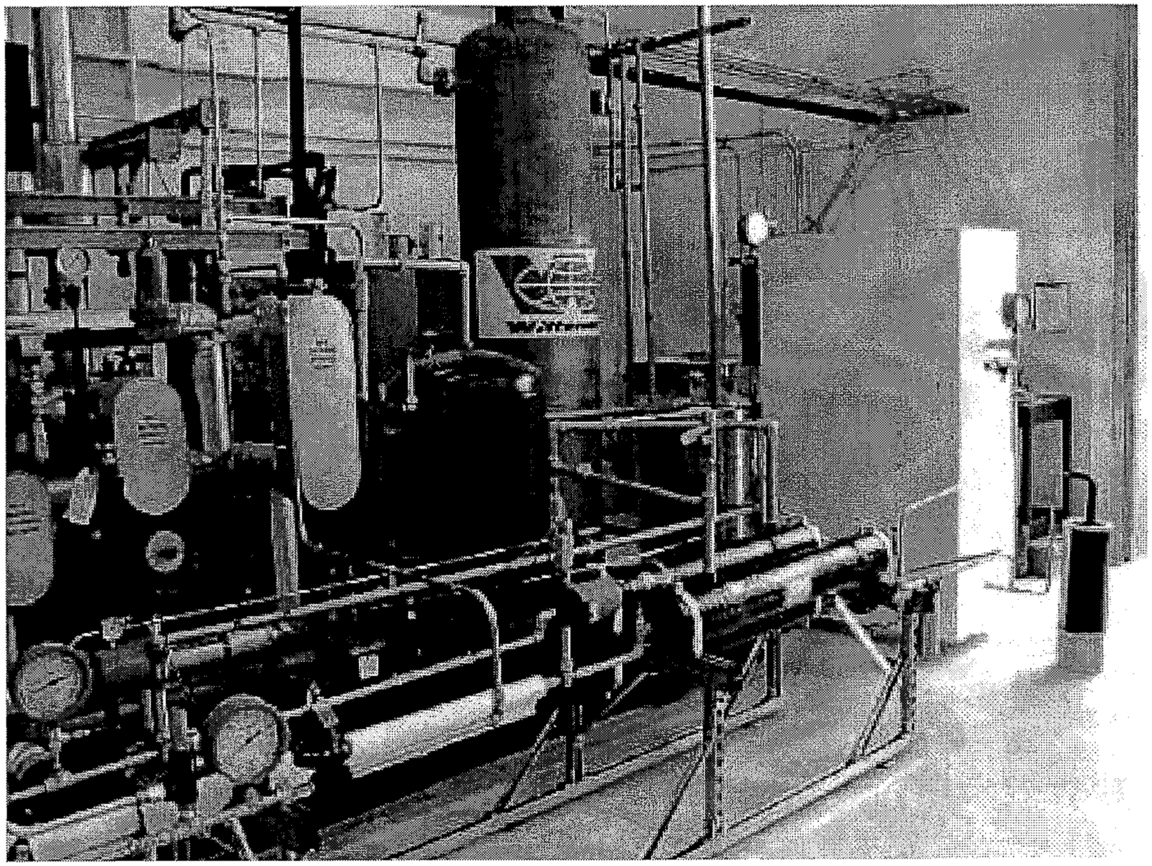
Acrion
Technologies

Landfill Snow (dry ice, -109°F)



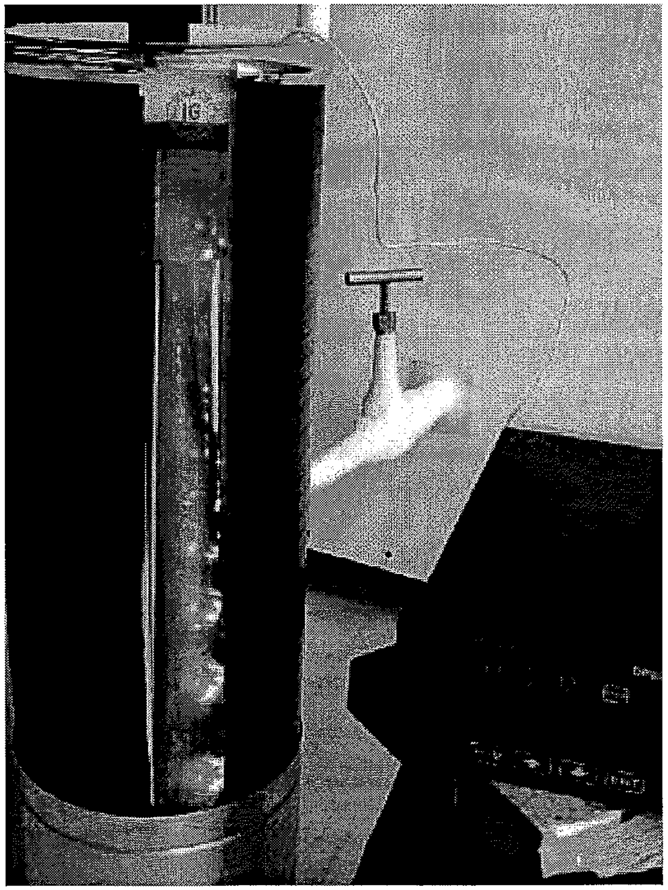
Acrion Technologies

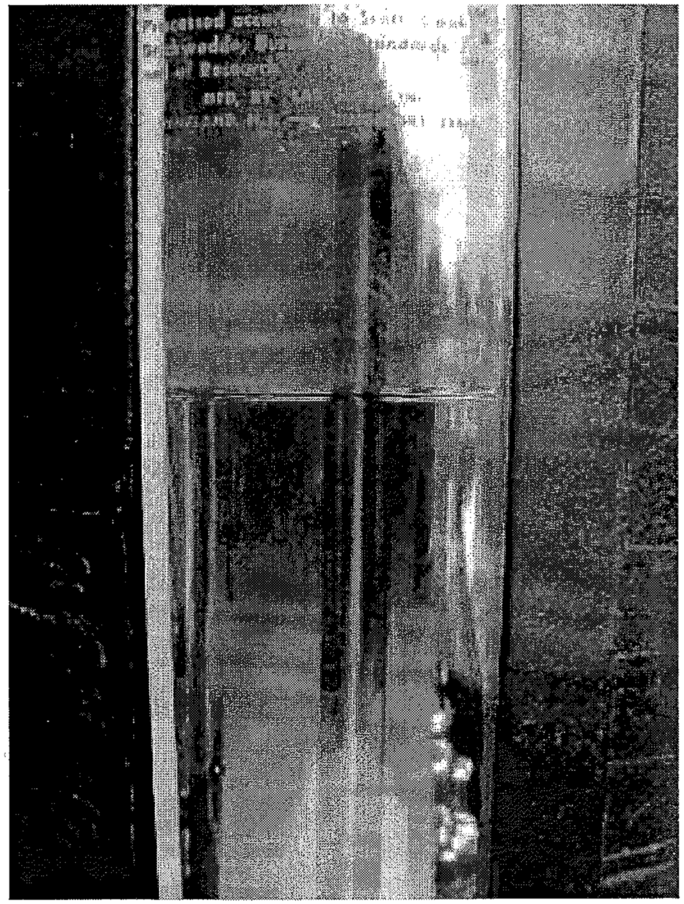
Refined to LNG



Acrion Technologies

Landfill LNG (-259°F)





Acrion
Technologies

2004 at NJ EcoComplex

- Make LM from LFG
- Fuel Two Mack Refuse Trucks
- Operate Trucks 500 Hours Each
- Engine Inspection / Diagnosis
- DOE / Burlington County / Mack
  Rutgers NJ EcoComplex / Acrion
  Chart / Air Products / WMI

Acrion
Technologies

Ballpark Estimates

(7th inning)

LFG, scfm	2,224	1,112	556
MMBtu/day	1,729	865	432
LM, gpd	20,000	10,000	5,000
LCO2, tpd	80	40	20
LM, ¢/gal (5 yr cap charge)	53	66	85
Diesel Equ, ¢/gal (untaxed)	90	112	145

Acrion
Technologies

LFG Alternative Fuels

<u>Physical Change:</u>

compress to **CNG** (CH_4, 3600 psi)

liquefy to **LNG** (CH_4, -259°F)

<u>Chemical Change:</u>

reform to **Hydrogen** (H_2)

react to **Methanol** (CH_3OH)

Bio Diesel (methyl ester)

Hydrogen (H_2)

react to **Dimethyl Ether** (CH_3OCH_3)

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Technologies

Acknowledgement

- ✓ US DOE NETL / SBIR Program
- ✓ US DOE Brookhaven National Lab
- ✓ New Jersey EcoComplex / Rutgers U
- ✓ Burlington County, NJ
- ✓ Mack Trucks, Allentown, PA

Acrion
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Directions:

a) New Jersey
b) I-295
c) Exit 52A / ¼ mile

Please Visit,

NJ EcoComplex
www.acrion.com

Thanks for Listening!

APPENDIX E

Landfill Gas to LNG and LCO_2
Final Report

7/22/04

LANDFILL GAS to LNG and LCO_2

FINAL REPORT

for
Calendar Year 2001

prepared for

Dr James Wegrzyn
Brookhaven National Laboratory
Upton, New York 11973

by

Jeff Cook, Larry Siwajek, William Brown

Acrion Technologies, Inc.
9099 Bank Street
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216 573 1185 / acrion@aol.com

February 20, 2002

ABSTRACT

Acrion, together with other organizations, is working with Brookhaven National Laboratory (BNL) to demonstrate liquid methane production from municipal landfill gas. BNL's ultimate goal is to power heavy duty trucks with liquid methane fuel. Acrion completed field demonstration of its CO2 Wash™ landfill gas (LFG) cleanup system at the New Jersey EcoComplex, Burlington County, New Jersey, in December 2001. Contaminant removal from LFG is a necessary first step in the preparation of landfill methane for liquefaction. Results obtained under this phase of work with BNL show conclusively that CO2™ Wash removes landfill gas contaminants to levels which will not interfere with downstream methane liquefaction. Forty-three contaminants found in Burlington's raw landfill gas were not detected in the product methane, including ***all*** siloxanes and halogenated compounds. Non-methane components detected in the methane/CO2 product stream were ethane + ethylene (5 ppm), propane (14 ppm), and carbonyl sulfide (0.1 ppm). Liquid methane vehicle fuel produced from LFG by CO2 Wash™ would be consistent quality with virtually no higher hydrocarbons or sulfur compounds. Fuel weathering is eliminated, engine performance is maintained, and tailpipe emissions are reduced. Acrion's efforts in 2002 will be directed toward development of a commercial scale landfill gas demonstration project based on CO2 Wash™ producing liquid methane heavy duty truck fuel.

TABLE OF CONTENTS

page

Abstract ii

Table of Contents iii

List of Figures iii

List of Tables iii

I. INTRODUCTION 1

II. COMMERCIAL PROJECT 1

III. PROCESS DEMONSTRATION UNIT 3

3.1 Purpose 3
3.2 Location 3
3.3 Description 5
3.4 Pre-Operation 8
3.5 Analytical Techniques 9

IV. ANALYTICAL RESULTS 11

4.1 Clean Fuel Product 11
4.2 Food Grade Liquid CO2 12

V. CONCLUSIONS 13

LIST OF FIGURES

Figure 1 Location of CO2 Wash™ Process Demonstration Unit 4

Figure 2 Schematic Process Flowsheet 6

LIST OF TABLES

Table 1 Landfill Gas Cleanup for Liquid Methane Production 3

Table 2 Gas Analysis Report / Raw LFG and Methane Product 12

Table 3 Gas Analysis Report / Raw LFG and Methane Product T0-14 Target List 13

Table 4 Gas Analysis Report / Raw LFG and Methane Product Non T0-14 Target List / Toxic Substances Sub-17 14

Table 5 Gas Analysis Report / CO2 Product 16

I. INTRODUCTION

This annual report for 2001 is the final deliverable under this phase of the contract. It presents work accomplished during the period May 1 through December 31, 2001 on two project tasks:

Task 1 Commercial project to make LNG from landfill gas, and

Task 2 Pilot plant operation to verify methane quality.

Acrion is one of several organizations cooperating with Brookhaven National Laboratory and Waste Management, Inc., to produce liquid methane transportation fuel from municipal landfill gas. Waste Management desires to convert its heavy duty refuse collection truck fleets, now almost exclusively diesel powered, to run on clean burning, renewable landfill methane. Waste Management has decided to develop its first commercial project producing liquid methane from landfill gas (LFG) at the Arden Landfill, Washington, Pennsylvania, about 25 miles southwest of Pittsburgh. Acrion's efforts with Waste Management are described in Section II.

Acrion's project role is to provide technology and equipment to clean landfill gas, i.e., remove trace contaminants from raw LFG so that they don't interfere and complicate downstream carbon dioxide removal and methane liquefaction. The performance capabilities of Acrion's landfill gas cleanup technology have been evaluated through construction and operation of a process demonstration test unit (PDU) located at the NJ EcoComplex, Burlington County Landfill, Mansfield Township, Columbus, New Jersey. NJ EcoComplex is staffed and administered by Rutgers University. A review of PDU analytical results is presented in Section III.

II. COMMERCIAL PROJECT

Waste Management (WM) envisions a commercial scale landfill gas conversion to LNG project at Arden Landfill, Washington, Pennsylvania. According to Paul Gagnon (8/20/02), WM's Manager of Technical Maintenance, Fuels & Emissions, WM "will do whatever it takes to supply quality LFG to the liquid methane project." Preliminary project design work assumes availability of 2500 standard cubic feet per minute (scfm) of LFG at Arden with composition 53% methane, 43% carbon dioxide, and 4% inert (mostly nitrogen, < 1% oxygen). Planned segregation of interior and perimeter gas extraction wells at Arden will help minimize air contamination of the feedstock LFG.

The process steps converting LFG to liquid methane are:

1) landfill gas collection and quality monitoring (WM)
2) landfill gas compression and dehydration (Acrion)
3) contaminant and bulk CO2 removal (Acrion);
4) residual CO2 removal to ppm levels (Salof);

5) methane liquefaction (Salof);
6) liquid methane storage and distribution (third party);
7) product sales and marketing (ALT Fuels).

WM has assembled a team of technology providers, including Acrion Technologies, Inc, and has selected a project developer. Acrion met project developer ALT Fuels, and a second technology provider, Salof Refrigeration, at a contract negotiation meeting at Arden Landfill on November 23, 2001. Acrion understands the project is proceeding along the following general outline:

- WM upgrades, operates and maintains gas collection system, assures gas quality;
- WM sells collected LFG to ALT Fuels and retains applicable tax credits;
- ALT Fuels finances , develops, owns and operates project;
- ALT Fuels sells liquid methane to WM at Arden, and sells excess liquid methane, if any, on the open market.

The principal action item from the November 23 meeting was WM's commitment to improve gas quality at Arden Landfill. WM is to investigate alternatives for improving gas quality including greater diligence in well field management, installation of additional wells, and segregation of existing wells. WM is to report on these efforts in January 2002.

Based on 2500 scfm of LFG feedstock with the above stated quality, i.e.,

53% methane,
43% carbon dioxide,
4% total inerts with < 1% oxygen,
dry basis

2500 scf/m x 60 m/HR x 24 HR/Dy = 3.6×10^6 scf/d
$3.6 \times 10^6 \times .53 = 1.908 \times 10^6$ scf/dy Methane
@ 53% CH_4 = 83,320 BTU/gal = 22,900 g/D

maximum liquid methane production is 22,900 gpd (100% methane recovery), and maximum liquid CO2 production is 90 tpd (100% CO2 recovery). Methane recovery from Acrion's contaminant and bulk CO2 removal step is virtually 100%. Methane losses are dependant on the performance of downstream process steps, final CO2 removal and methane liquefaction, and the degree of process integration achieved through recycle of methane slip streams. Liquid methane production may be decreased if a portion of the feedstock is used to produce power for rotating equipment. Carbon dioxide recovery in Acrion's cleanup step is about 45%, or 40 tpd of liquid CO2 product. Recovery could be increased significantly by recycle to Acrion of carbon dioxide off gas from the final CO2 removal step. As the project evolves, Acrion and possibly other project participants will decide if economics and market opportunity justify recovery of merchant liquid carbon dioxide as a second product.

Preliminary specifications of Acrion's cleanup step communicated to project developer ALT Fuels on August 21, 2001, are shown below in Table 1.

7. Feed Gas N
Product Gas

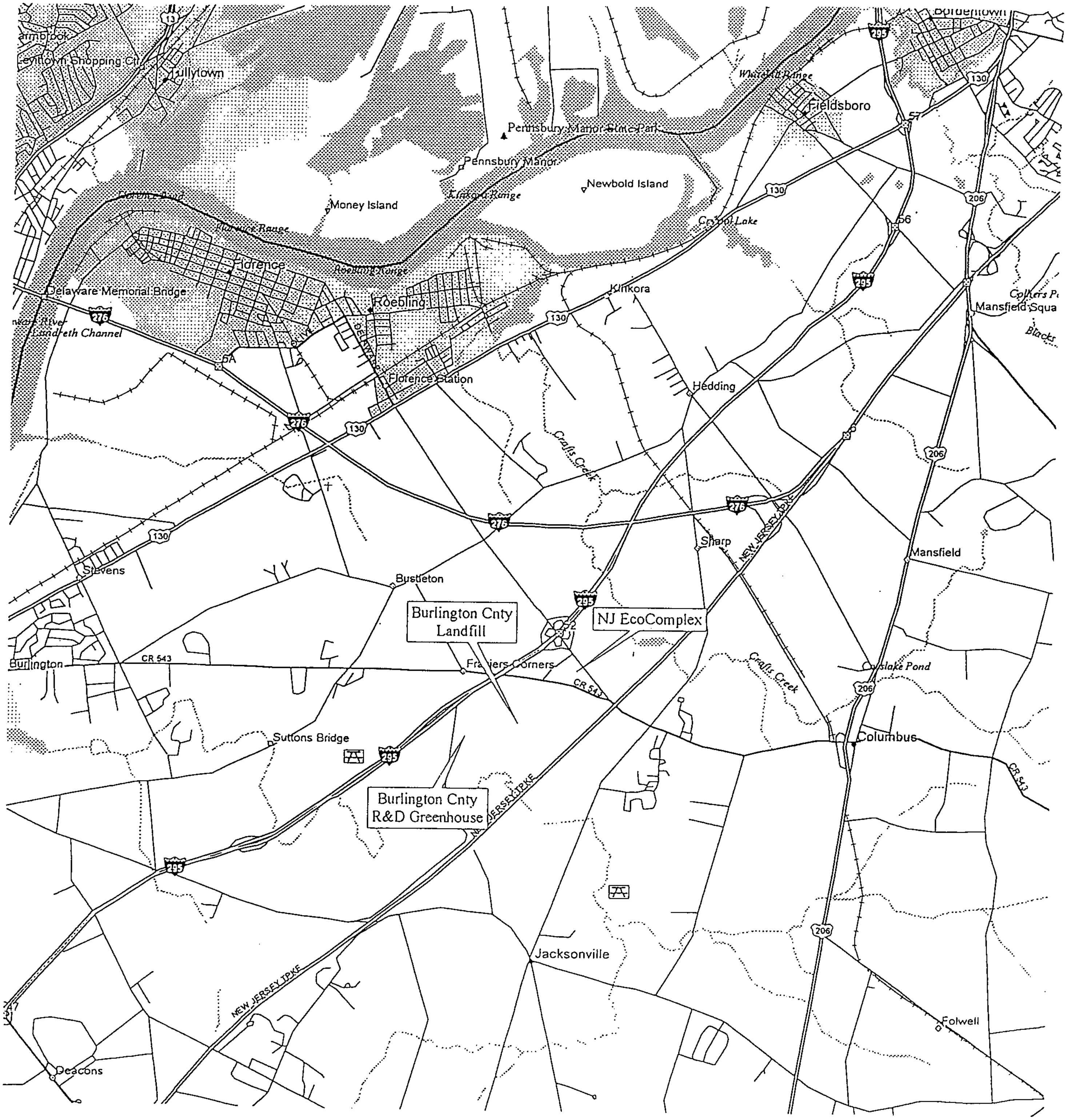
Table 1 Landfill Gas Cleanup for Liquid Methane Production	
Feed Gas	2,500 scfm; 53% methane, 43% carbon dioxide, 4% nitrogen, water sat'd
Product Gas 7.	1,~~950 s~~cfm; 73% methane + inerts, 27% carbon dioxide, water < 0.1ppm; contaminants < 0.5 ppm total (except H_2S, ethane, propane) pressure 400 psia; temperature up to 85°F
Power	700kW, including LFG compression, pumps, misc; essentially no consumables
Capital Cost	$1.8 million (the cost increases if CO_2 content of the feed gas decreases below about 40% or inerts rise above about 5%)
Option	Acrion retains option to recover and sell liquid CO_2 at our incremental cost; minimum of 40 tpd liquid CO_2 at 300 psia, 0°F

III. PROCESS DEMONSTRATION UNIT

3.1 Purpose: The Process Demonstration Unit (PDU) embodies Acrion's patented CO_2 Wash™ contaminant removal technology to produce clean methane (75% methane, 25% carbon dioxide, contaminant-free, 50 million Btu/day) and food grade liquid CO_2 (up to 1 ton per day). PDU operation allowed independent analytical testing of product quality and industry evaluation, essential activities for commercialization of the technology. A portion of the product liquid CO_2 may be supplied to the Burlington County R&D Greenhouse (on-site) for plant fertilization. In addition to quantitative analysis of the clean methane stream under this current Brookhaven contract to determine its suitability for methane liquefaction, fuel cell manufacturers have expressed interest to monitor and evaluate methane purity to determine its suitability for catalytic reformation to hydrogen, and membrane packagers have inquired about installing CO_2 removal capability to the PDU to further upgrade Acrion's CO_2 Wash™ methane product, i.e., the residual CO_2 removal step required prior to methane liquefaction.

3.2 Location: The PDU is located at the New Jersey EcoComplex, a new facility erected by the State of New Jersey at the Burlington County Resource Recover Complex, Columbus, New Jersey. In addition to the NJ EcoComplex, the Resource Recovery Complex includes a municipal sanitary landfill, recycling center, hazardous materials collection center, composting facility, and a state-of-the-art one acre research and demonstration greenhouse. Both the EcoComplex and the R&D greenhouse are staffed, operated and administered by Rutgers University. NJ EcoComplex is located about ¼ mile east of I-295, exit 52A, Columbus (Figure 1).

Figure 1
New Jersey EcoComplex of Rutgers University
Location of Acrion's CO2 Wash™ Process Demonstration Unit



Description: Acrion's landfill gas cleanup PDU is the result of US DOE SBIR grant DE-FG02-98ER82516, Phase II, cost shared 57% DOE, 26% Burlington County/Rutgers/Others, 17% Acrion. Expenditures through December 31, 2001, total over $1.34 million. A schematic PDU flowsheet is shown in Figure 2. The PDU comprises four interconnected equipment skids: 1) process skid, 2) compression skid, 3) refrigeration skid, and 4) liquid CO2 storage tank. A photo of the process skid, located inside the NJ EcoComplex, is shown in Figure 3. A photo of the compression skid, refrigeration skid, and liquid CO2 storage tank, located outside, is shown in Figure 4. The process skid and refrigeration skid were built to Acrion's specifications by the Wittemann Company, Palm Coast, Florida. Wittemann supplies CO2 recovery, generation and liquefaction equipment to customers worldwide. The compression skid, originally designed for compressed natural gas service, was purchased used from J-W Operating Company, Oklahoma City, Oklahoma. As part of the purchase agreement, J-W refurbished and painted the compression skid, and demonstrated its operation to Acrion's satisfaction in Oklahoma City. J-W's primary business is supplying compression equipment to the oil and gas industry. The liquid CO2 storage tank, purchased by Acrion from Liquid Carbonic in 1994, can hold approximately 6 ton of liquid CO2 at commercial storage and distribution conditions, 300 psia and 0°F.

The PDU process steps are:

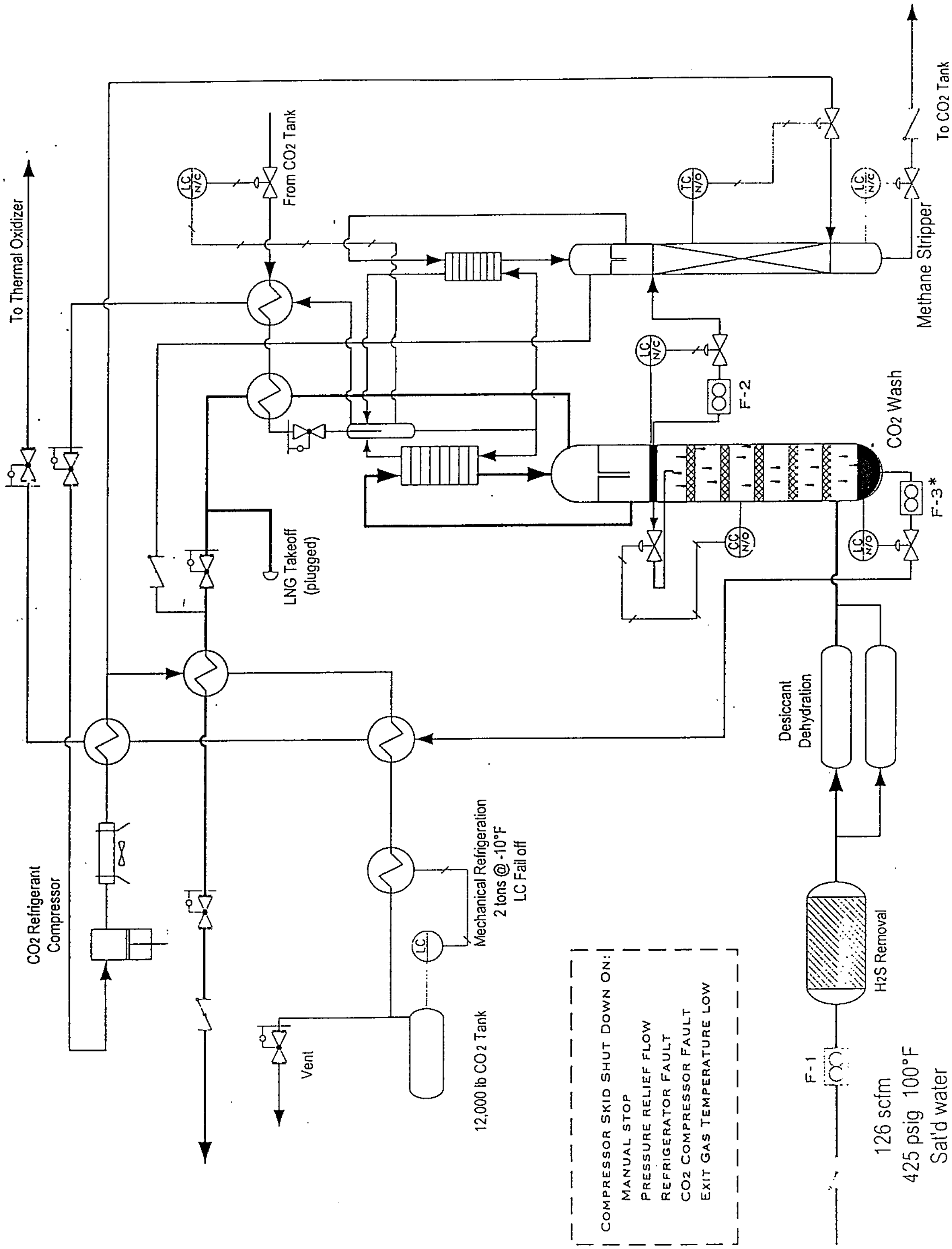
1) landfill gas compression to 400 psi and bulk water knock out;
2) hydrogen sulfide removal with SulfaTreat adsorbent;
3) dehydration;
4) contaminant removal by Acrion's CO2 Wash™ technology;
5) methane stripping from liquid CO2 product;
6) integrated CO2 refrigeration system;
7) liquid CO2 product storage.

Landfill gas is provided by Burlington County through a 6-inch plastic pipe extending approximately 500 feet from the perimeter gas collection line at the landfill to the rear of the EcoComplex. A blower system installed by the county can deliver up to 300 scfm landfill gas at about 40" water column. Acrion's PDU processes approximately 100 scfm. more like 65

Landfill gas is compressed with a three stage, reciprocating Knox-Western compressor rated at 75 hp; the compressor draws about 35 kW (47 hp) during PDU operation and discharges LFG at about 420 psi. Gas cooling and water knock-out occur after each stage of compression.

A SulfaTreat vessel operating at 410 psia removes hydrogen sulfide from LFG. Discharge LFG contains less than 0.1 ppm hydrogen sulfide, and vessel changeout time is about 4 to 6 months assuming continuous operation with 50 ppm max H2S in the LFG feed. Analysis of Burlington LFG taken about 6 months prior to operation indicated 40 ppm H2S.

Figure 2
Schematic Process Flowsheet
Acrion's CO2 Wash™ Process Demonstration Unit



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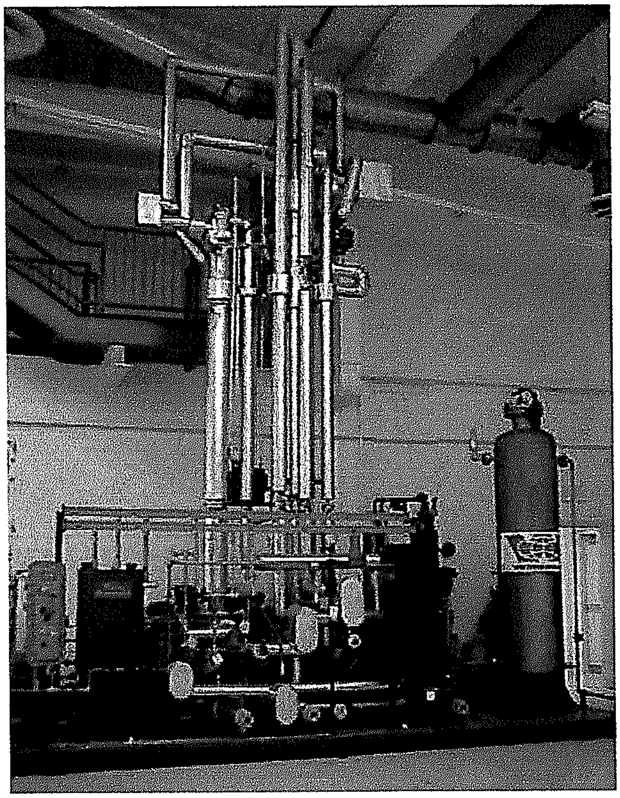


Figure 3
CO2 Wash™ Process Skid, NJ EcoComplex

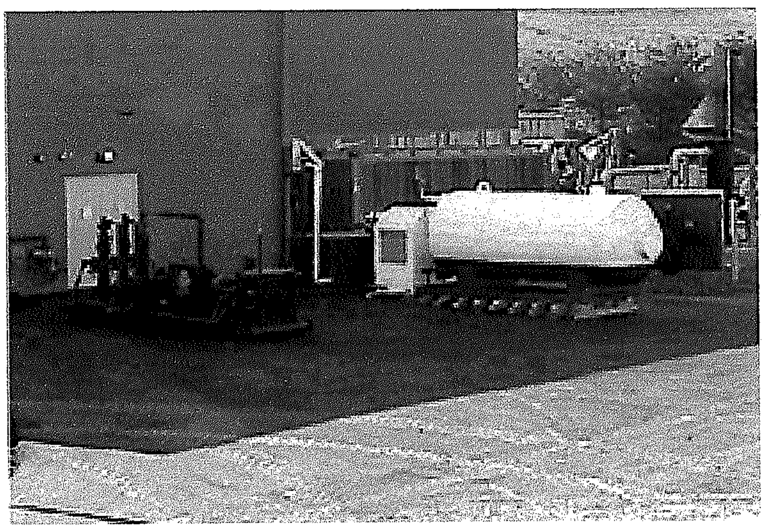


Figure 4
Compression, Refrigeration, CO2 Storage Skids, NJ EcoComplex

A pressure swing adsorption (PSA) dehydration system removes water to about -100°F water dewpoint (at 1 atm). The adsorbent solid is alumina, the PSA cycle time is 2 minutes, and regeneration of the wet bed is accomplished with dry LFG.

H2S-free, dry landfill gas next enters the CO2 Wash™ tower where contaminants are removed with liquid CO2 sorbent. The column is 6 inches diameter with 10 feet of packing (structured stainless steel mesh packing). Liquid CO2 condenses from LFG at the column top and accumulates on the top tray. A portion of this liquid CO2 is sent down the column to absorb LFG contaminants. The remaining liquid CO2 is withdrawn from the column as product. A small stream of liquid CO2 sorbent containing absorbed contaminants is withdrawn from the column bottom, vaporized, and sent by a return line to the landfill gas collection system, and eventually, to the landfill flare. The amount of CO2 in this contaminant stream is about 25% of the CO2 contained in the raw LFG feed. Clean product methane is withdrawn from the column top, containing 75% methane, 25% CO2, plus any nitrogen and oxygen present in the raw landfill gas feed. Methane in this stream, after a final CO2 removal step which is not part of the current demonstration, becomes feedstock for liquefaction. The current PDU configuration returns this methane stream to the landfill gas collection system. Acrion has no plans to use this clean methane for any purpose other than verification of product quality by gas analysis in the current demonstration program.

Liquid CO2 product from the top tray of the wash tower proceeds to a stripper tower where light ends (principally methane) are removed. Product CO2 leaves the stripper tower bottom as cold high pressure food grade liquid CO2 ready for storage and eventual distribution. Stripped methane is mixed with product gas for return to the landfill gas collection system. A commercial process configuration to produce liquid methane would recycle stripped methane to an intermediate stage of compression at the front of the process for recovery, or use this methane as process fuel if needed.

In summary, the PDU accepts up to 100 scfm of raw landfill gas, and treats the raw LFG to produce three output streams: 1) clean contaminant-free methane-enriched landfill gas (75% methane, 25% carbon dioxide, no contaminants) which is returned to the landfill flare for incineration; 2) up to 1 ton per day of food grade liquid CO2 (300 psia, 0°F) sent to on-site storage; and 3) a small stream of gaseous CO2 containing contaminants which is also returned to the landfill flare for incineration.

3.4 Pre-Operation: The PDU skids were installed, interconnected, landfill gas supply and return lines installed, and components individually checked out. This work was accomplished during the period December, 2000 through August, 2001, with Acrion crews working about 40% time at the New Jersey EcoComplex demonstration site.

The PDU was operated continuously at steady-state with pure CO2 feed gas for periods of several hours and then routinely shut down. The purpose of these initial runs with CO2 was to verify operation of the PDU refrigeration system, verify attainment of design temperatures and pressures, and insure formation of liquid CO2 inventories at appropriate locations in the process.

A considerable portion of Acrion's effort during August and September was spent de-bugging the LFG blower system and condensate return lines. Though not part of Acrion's responsibilities, the lack of timely support from the blower contractor required that Acrion become intimately involved. Problems detected and cured included identification of major air leaks, inoperable instrumentation, and discovery that the main condensate drainage line had been capped prior to burial. Acrion was the primary work force in bringing the blower system to normal operational status.

3.5 Analytical Techniques: The focus of this effort was measurement of trace contaminants in the raw LFG feedstock, product methane and product liquid CO2. Gas sample ports were placed throughout the PDU. Key sample locations used for this effort were: raw LFG at blower outlet, high pressure LFG upstream of the SulfaTreat vessel, product methane after cooling recovery, and liquid CO2 product at the bottom of the stripper column. Acrion monitored gas compositions with three instruments: 1) a portable Landtech 90 unit, 2) a Toxirae handheld monitor, and 3) an HP 6890 GC.

Landtech 90 simultaneously and instantaneously determines and displays the major components of LFG: CH4, CO2, nitrogen and oxygen. Landtech 90 was used to monitor inlet LFG composition in general and to guard against high oxygen levels. Landtech 90 also gave a rough measure of the process effectiveness by displaying the CO2 and CH4 content of product gas in real time.

The Toxirae handheld monitor utilizes photo ionization to measures total VOC's which are reported as concentration of benzene that generates an equivalent response; it's detection limit is about 0.1 ppm. This real time device was primarily used to provide a qualitative measure of the VOC content in the raw landfill gas, generally 5 to 20 ppm as benzene. Analysis of the product gas would generally show the absence of contaminants with readings of 0.0 ppm. Because product gas contamination was thought to be in the ppb range, true quantitative analysis of the product gas with this device was not possible.

The HP 6890 GC is equipped with an electron capture detector (ECD) and a thermal conductivity detector (TCD). ECD detects chlorinated hydrocarbons in the parts per billion (ppb) range, while TCD gives percentage readings of CO2 and methane in the product. The GC, which requires 10 to 15 minutes per sample, easily detects the presence of halogenated contaminants but provides no identification of individual compounds. One halogenated compound detected in the product gas had retention time characteristic of refrigerant R-12. This compound, present in low ppb's, was used to monitor the effect of variable CO2 absorbent flows on contaminant removal, i.e., increasing the flow of liquid CO2 absorbent down the CO2 Wash™ tower caused the concentration of this halogenated compound in the product gas to drop, and vice versa.

During PDU operation, gas samples were also collected in stainless steel cylinders for analysis by an independent firm, Atlantic Analytical Laboratory (AAL), Whitehouse, New Jersey. Cylinders were filled with samples at operating pressure and delivered within 24 hours AAL's New Jersey lab. The cylinder holding clean methane product samples had a thin interior coating of silicon dioxide (glass) to minimize reactive or catalytic destruction of contaminants, an important consideration when attempting to identify compounds at the parts per billion level.

Cylinders carrying feed LFG were not internally coated because contaminants were in the ppm range. Any decrease in contaminant levels would be slight or un-measurable over the short transport and analysis times. Also, a decrease in contaminants measured in the feed would not create artificial advantage for PDU performance, rather the opposite.

Siloxanes were measured by bubbling a known quantity of gas (target - 10.0 liters) through 50 ml of methanol chilled in an ice bath over the course of an hour. In glassware constructed to maximize gas-liquid contact. the methanol absorbed siloxanes (along with other contaminants), thereby concentrating them. The methanol was transported within 24 hours in a sealed glass container to AAL where siloxanes were identified by GC/MS.. The amount of siloxanes in the methanol allows calculation of the concentration in the original gas sample. Analysis of raw landfill gas at the blower confirmed the presence of siloxanes. Analysis of CO2 Wash ™product gas confirmed the absence of siloxanes in product gas.

Independent of analytical gas sampling techniques was a Sierra Gas monitoring system which continuously scanned the ambient indoor laboratory air for methane or other flammable gases, and for oxygen deficiency. It would trigger an alarm before conditions became unsafe for personnel or property. Except for brief periods during calibration, the Sierra gas monitor detected no alarm conditions.

3.6 Operation: The PDU was prepared to process raw landfill gas feedstock. Operation began Tuesday, September 25, 2001, and continued intermittently until Tuesday, December 11, 2001. More than sufficient run time was logged to demonstrate reliable operation under full automatic control, and to verify the quality of methane and liquid CO2 products. On Tuesday, September 25, 2001 the PDU was started and operated routinely. The unit reached operating pressure about 10 minutes after compressor startup, at which time liquid CO2 began to condense from LFG. Within 30 minutes of startup, methane product was leaving the CO2 Wash™ column substantially free of contaminants as indicated by the Toxirae VOC monitor. After one hour operation the PDU reached steady state as indicated by an isothermal CO2 Wash™ column producing a steady flow of contaminated CO2 from the bottom. No liquid CO2 was withdrawn from the top as co-product. Two samples were taken for siloxane analysis: raw landfill gas from the blower exit, and product methane from the CO2 Wash™ column.

The PDU was operated in a similar but longer duration run on Thursday, September 27. Sample cylinders were filled with gas samples taken at the inlet to the SulfaTreat vessel (compressed, partially dehydrated landfill gas), and from the product methane line.

In October the methane stripper was modified to improve the flow of CO2 stripping gas, and insure consistent production of liquid CO2. A problem with underground condensate drainage lines prevented significant PDU operation for the remainder of October. This problem, directly attributed to faulty installation by the blower contractor, was resolved only after backhoe excavation of the blower condensate drainage line to remove a test cap and connect the condensate drain line to the sewer sump.

During the period Friday, November 9 through Tuesday, November 13, the Acrion personnel operated the PDU, mostly under automatic control, for approximately 100 hours, producing both clean methane and clean liquid CO2. Over 3000 lb mass of four 9's (>0.9999 pure) liquid CO2 were produced during this period, believed to be the first liquid CO2 of any purity ever produced from raw landfill gas. Samples of the methane and liquid CO2 products were taken for independent testing by AAL. A follow up run in which the ratio of liquid CO2 absorbent to LFG feed was systematically varied produced more samples for analysis.

PDU operation on Monday, December 10 and Tuesday, December 11 was for the benefit of commercial and industrial parties interested in high value products from LFG, and for Acrion's DOE SBIR project officers. Many Waste Management employees, including Paul Gagnon, witnessed PDU operation. Other parties included Air Products, Mack Trucks, Praxair and Specialty Minerals. Air Products and Mack Trucks are primarily interested in the production of liquid methane; Praxair and Specialty Minerals in recovery of CO2.

At the end of operation on Tuesday, December 11, the PDU was purged with CO2, powered down and secured. The PDU is ready to operate with a day or two of review and checkout.

IV. ANALYTICAL RESULTS

<u>4.1 Clean Fuel Product:</u> During PDU operation, on-site composition analysis was used to qualitatively monitor process effectiveness by observing the presence or absence of VOC's in the product gas using the Toxirae. These measurements were preliminary confirmation of PDU performance and signaled when steady state operation had been achieved. Gas samples for independent, off-site analysis were then collected. Atlantic Analytical Laboratory performed the standard EPA analysis procedure for LFG contaminants, T0-14 (tee zero fourteen), on the raw landfill gas feed and the methane product gas. Also the methane product gas was analyzed using an enhanced T0-14 procedure, sub section 17, to detect compounds in the ppb range. Both gases were analyzed for sulfur compounds and for bulk composition. Silicon containing contaminants were examined after on site sample preparation as described earlier.

AAL's analysis of the raw LFG, Tables 2, 3 and 4 (Raw Landfill Gas, AAL 6061-1), shows a menu of contaminants typical of most landfills. Thirteen of sixteen VOC's detected on the T0-14 target list (Table 3) were also present in raw landfill gas at Al Turi Landfill, Goshen, New York, site of Acrion's first field demonstration of CO2 Wash™ in 1997-98. The nine sulfur species identified in Table 2 are among the principal compounds which impart a distinctive odor to landfill gas. The non T0-14 target list (Table 4) identifies the 10 most abundant trace compounds in the samples which are not on EPA's T0-14 target list.

Table 2
GAS ANALYSIS REPORT
by ATLANTIC ANALYTICAL LABORATORY (AAL, Whitehouse, NJ)
ACRION'S CO2 WASH PROCESS DEMONSTRATION UNIT

	Raw Landfill Gas AAL 6061-1			Methane Product AAL 6061-3	
Non-Condensable Gases	vol%		DL vol%	vol%	
Nitrogen	6.7	7.3°	0.01	9.6	9.8°
Oxygen	--		0.10	--	
Hydrogen	--		0.10	--	
Carbon Dioxide	35.0	38.3°	0.01	25.7	26.3°

° - Normalized to 100%

Volatile Hydrocarbons	ppm volume		DL ppm	ppm volume	
Methane	(49.6%)	(54.3%)°	1	(62.6%)	(63.9%)°
Ethylene	3		1	3	
Acetylene	nd		10	nd	
Ethane	2		1	2	
Propylene	nd		1	nd	
Propane	41		1	14	
Isobutane	13		1	nd	
n-Butane	8		1	nd	
Butenes	nd		1	nd	
Isopentane	2		1	nd	
n-Pentane	2		1	nd	
Hexanes +	200		1	nd	

Volatile Sulfur Compounds	ppm volume	DL ppm	ppm volume
Hydrogen Sulfide	nd	0.05	nd
Carbonyl Sulfide	1.10	0.05	0.1
Sulfur Dioxide	nd	0.05	nd
Methyl Mercaptan	nd	0.05	nd
Ethyl Mercaptan	nd	0.05	nd
Dimethyl Sulfide	4.00	0.05	nd
Carbon Disulfide	0.46	0.05	nd
Isopropyl Mercaptan	nd	0.05	nd
Methyl Ethyl Sulfide	0.06	0.05	nd
n-Propyl Mercaptan	nd	0.05	nd
t-Butyl Mercaptan	0.26	0.05	nd
Dimethyl Disulfide	1.00	0.05	nd
sec-Butyl Mercaptan	0.16	0.05	nd
Isobutyl Mercaptan	0.26	0.05	nd
Diethyl Sulfide	nd	0.05	nd
n-Butyl Mercaptan	0.12	0.05	nd

Table 3
GAS ANALYSIS REPORT
by ATLANTIC ANALYTICAL LABORATORY (AAL, Whitehouse, NJ)
ACRION'S CO2 WASH PROCESS DEMONSTRATION UNIT

	Raw Landfill Gas AAL 6061-1		Methane Product AAL 6061-3
GC/MS Results TO-14 Target List	ppm volume	DL ppm	ppm volume
Freon-12	2.8	0.5	nd
Methyl Chloride	nd	0.5	nd
Freon-114	0.5	0.5	nd
Vinyl Chloride	0.5	0.5	nd
Methyl Bromide	nd	0.5	nd
Ethyl Chloride	nd	0.5	nd
Freon-11	nd	0.5	nd
Vinylidene Chloride	nd	0.5	nd
Freon-113	nd	0.5	nd
Dechloromethane	nd	0.5	nd
1,1-Dichlorethane	nd	0.5	nd
cis-1,2-Dichloroethylene	1.2	0.5	nd
Chloroform	nd	0.5	nd
1,1,1-Trichloroethane	nd	0.5	nd
1,2-Dichlorethane	nd	0.5	nd
Benzene	0.8	0.2	nd
Carbon Tetrachloride	nd	0.5	nd
1,2-Dichloropropane	5.1	0.5	nd
Trichloroethylene	0.7	0.2	nd
cis-1,3-/Dichloropropylene	nd	0.5	nd
trans-1,3-Dichloropropylene	nd	0.5	nd
Toluene	38.0	0.2	nd
1,1,2-Trichloroethane	nd	0.2	nd
1,2-Dibromoethane	nd	0.5	nd
Tetrachloroethylene	1.5	0.2	nd
Chlorobenzene	nd	0.2	nd
Ethyl Benzene	14.0	0.2	nd
m+p-Xylenes	15.0	0.2	nd
Styrene	4.4	0.2	nd
o-Xylene	4.2	0.2	nd
1,1,2,2-Tetrachloroethane	nd	0.2	nd
4-Ethyltoluene	6.2	0.2	nd
1,3,5-Trimethylbenzene	1.2	0.2	nd
1,2,4-Trimethylbenzene	1.2	0.2	nd
1,3-Dichlorobenzene	nd	0.2	nd
1,4-Dichlorobenzene	nd	0.2	nd
Benzylchloride	nd	0.2	nd
1,2-Dichlorobenzene	nd	0.2	nd
1,2,4-Trichlorobenzene	nd	0.2	nd
Hexachlorobutadiene	nd	0.2	nd

Table 4
GAS ANALYSIS REPORT
by ATLANTIC ANALYTICAL LABORATORY (AAL, Whitehouse, NJ)
ACRION'S CO2 WASH PROCESS DEMONSTRATION UNIT

	Raw Landfill Gas AAL 6061-1		Methane Product AAL 6061-3
GC/MS Results Non-TO-14 Target List	**ppm volume**	**DL ppm**	**ppm volume**
Propane	41		14
Isobutane	13	0.5	nd
Acetone	21	0.5	nd
Methylethyl Ketone	40	0.5	nd
2-butanol	38	0.5	nd
C6H12O2	28	0.5	nd
C9 Aliphatic Hydrocarbon	32	0.5	nd
Alpha-Pinene	38	0.5	nd
C11 Aliphatic Hydrocarbon	16	0.5	nd
D-Limonene	15	0.5	nd
GC/MS Results Toxic Substances Sub-17	**ppb volume**	**DL ppb**	**ppb volume**
Freon-12	Compounds detected with other test methods. Analysis at ppb level not performed.	10	nd
Vinyl Chloride		10	nd
Chloroform		10	nd
1,2-Dichloroethane		10	nd
Benzene		10	nd
Carbon Tetrachloride		10	nd
Trichloroethylene		10	nd
1,4-Dioxane		10	nd
1,1,2-Trichloroethane		10	nd
1,2-Dibromoethane		10	nd
Tetrachloroethylene		10	nd
1,1,2,2 Tetrachloroethane		10	nd
Methylene Chloride		10	nd
1,1,1-Trichloroethane		10	nd

NOTES:

AAL 6061-1: raw landfill gas after compression to 400 psig and water knockout
AAL-6061-3: methane product gas from CO_2 Wash
DL = Detection Limit, if not shown, reported result is greater than DL
nd = concentration is less than stated DL
-- = test not performed
ppm = parts per million
ppb = parts per billion

The above Tables 2, 3 and 4 also show the purity of product methane (Methane Product AAL 6061-3). Forty-three undesirable compounds found in Burlington's raw landfill gas were not detected in the product methane, including all siloxanes and halogenated compounds. The clean methane/CO2 mix contains only compounds that are found in natural gas: ~10% nitrogen, 5 ppm ethane and ethylene combined, 14 ppm propane and 0.1 ppm COS. With lower nitrogen achieved by better management of the gas collection system, and downstream rejection of residual CO2, this CO2 Wash™ product would yield 99.99% liquid methane without low temperature distillation. Liquid methane vehicle fuel produced from LFG by CO2 Wash™ would be of consistent quality with virtually nil higher hydrocarbons or sulfur compounds. Concern over fuel weathering vanish, engine performance is maintained, and tailpipe emissions are reduced. The methane product gas direct from CO2 Wash™, without any further CO2 removal, is pure enough for fuel cell hydrogen or for improved electric generation with reciprocating IC engines. Either of these two alternative uses for clean landfill gas could provide power for a small-scale liquefier.

4.2 Food Grade Liquid CO2: The co-production of a commercial grade liquid CO2 enhances process economics and further reduces greenhouse gas emissions from landfills. The analytical results from AAL listed in Table 5 demonstrate the ability of CO2 Wash™ to produce food grade liquid CO2 able to satisfy commercial users other than the major soft drink bottlers. Acrion's target market for liquid CO2 produced from LFG does not include beverage makers, but instead dry ice or refrigerant, greenhouses, paper manufacture, waste water treatment and other industrial uses. Acrion is working with several organizations primarily interested in landfill gas as a source of local, inexpensive CO2.

Commercial grade CO2 (Commercial CO2 AL 6556-2) bought from a local NJ supplier and CO2 produced from LFG (Acrion CO2 Product AAL 6695) are compared in Table 5. Purchased CO2 contains trace quantities of methane, ethane, nitrogen, oxygen and *methanol*. Liquid CO2 product from CO2 Wash™ contains propane (67 ppm) and COS (0.25 ppm, below food grade spec of 0.5 ppm). All other contaminants detected in the raw LFG are not found in the liquid CO2 product from CO2 Wash™. Propane, non hazardous to health at even higher concentrations, is usually kept below 10 ppm when the CO2 is used to carbonate soft drinks.

LFG CO2 was not analyzed for inerts such as nitrogen because the absence of methane indicates that any lower boiling gases were removed in the stripper. Oxygenates such as methanol were not investigated in the LFG CO2 because they are washed down as easily as benzene in the CO2 Wash absorber. The absence of benzene at 5 ppb indicates that oxygenates were removed in the CO2 Wash™ column to less than the 200 ppb detection limit. Also, among oxygenates, only acetone and 2-butanol were detected in the raw LFG. Benzene and R-12 would not be expected in commercial CO2, especially R-12, because of the CO2 source, e.g. ammonia plants, refineries, fermentation or natural well hence, no tests looked for these compounds.

Table 5
GAS ANALYSIS REPORT, CO2 PRODUCT
by ATLANTIC ANALYTICAL LABORATORY (AAL, Whitehouse, NJ)
ACRION'S CO2 WASH PROCESS DEMONSTRATION UNIT

TEST SPECIES	Commercial CO2 AAL 6556-2 ppm volume	DL ppm	Acrion CO2 Product AAL 6695 ppm volume
Hydrocarbons			
Methane	1.0	1	nd
Ethylene	nd	1	nd
Ethane	1.0	1	nd
Propylene	nd	1	nd
Propane	nd	1	67
Isobutane	nd	1	nd
n-Butane	nd	1	nd
Butene	nd	1	nd
Isopentane	nd	1	nd
n-Pentane	nd	1	nd
Non Condensables			
Nitrogen	26.0	1	-
Oxygen	7.0	1	-
Argon	nd	1	-
Hydrogen	nd	1	-
Helium	nd	1	-
Trace Contaminants			
Benzene	-	0.005	nd
Vinyl Chloride	nd	0.5	nd
R-12	-	0.5	nd
Sulfur Species			
Hydrogen Sulfide	nd	0.05	nd
Carbonyl Sulfide	nd	0.05	0.25
Sulfur Dioxide	nd	0.05	nd
Methyl Mercaptan	nd	0.05	nd
Ethyl Mercaptan	nd	0.05	nd
Dimethyl Sulfide	nd	0.05	nd
Carbon Disulfide	nd	0.05	nd
Isopropyl Mercaptan	nd	0.05	nd
Methyl Ethyl Sulfide	nd	0.05	nd
n-Propyl Mercaptan	nd	0.05	nd
t-Butyl Mercaptan	nd	0.05	nd
Dimethyl Disulfide	nd	0.05	nd
sec-Butyl Mercaptan	nd	0.05	nd
Isobutyl Mercaptan	nd	0.05	nd
Diethyl Sulfide	nd	0.05	nd
n-Butyl Mercaptan	nd	0.05	nd
Oxygenates			
Acetaldehyde	nd	0.2	-
Dimethyl Ether	nd	0.2	-
Ethylene Oxide	nd	0.2	-
Methanol	3.0	0.3	-
Acetone	nd	0.3	-
Ethanol	nd	0.3	-
Isopropanol	nd	0.3	-

V. CONCLUSION

Acrion has investigated production of liquid methane from landfill gas (LFG) for more than a decade. During the past several years, direction and assistance from BNL has noticeably raised the confidence level of industrial stakeholders in the viability Acrion's LFG cleanup technology. Operation of Acrion's second pilot demonstration unit at the NJ EcoComplex permitted detailed analytical testing of landfill gas products by an independent laboratory (Atlantic Analytical Laboratory, Whitehouse, NJ). CO2 Wash removed halogenated, siloxane, sulfur and non-methane organic contaminants from LFG to levels below one part per million (ppm) aggregate. Landfill gas contaminants will not block BNL's and industry's quest to source LNG from LFG.

APPENDIX F

- SWACO Equipment as of July 13, 2004
- LNG Tank Size and Weight Versus Diesel and CNG Tanks of Equivalent Fuel Gallonage

SWACO Equipment - 07-13-04

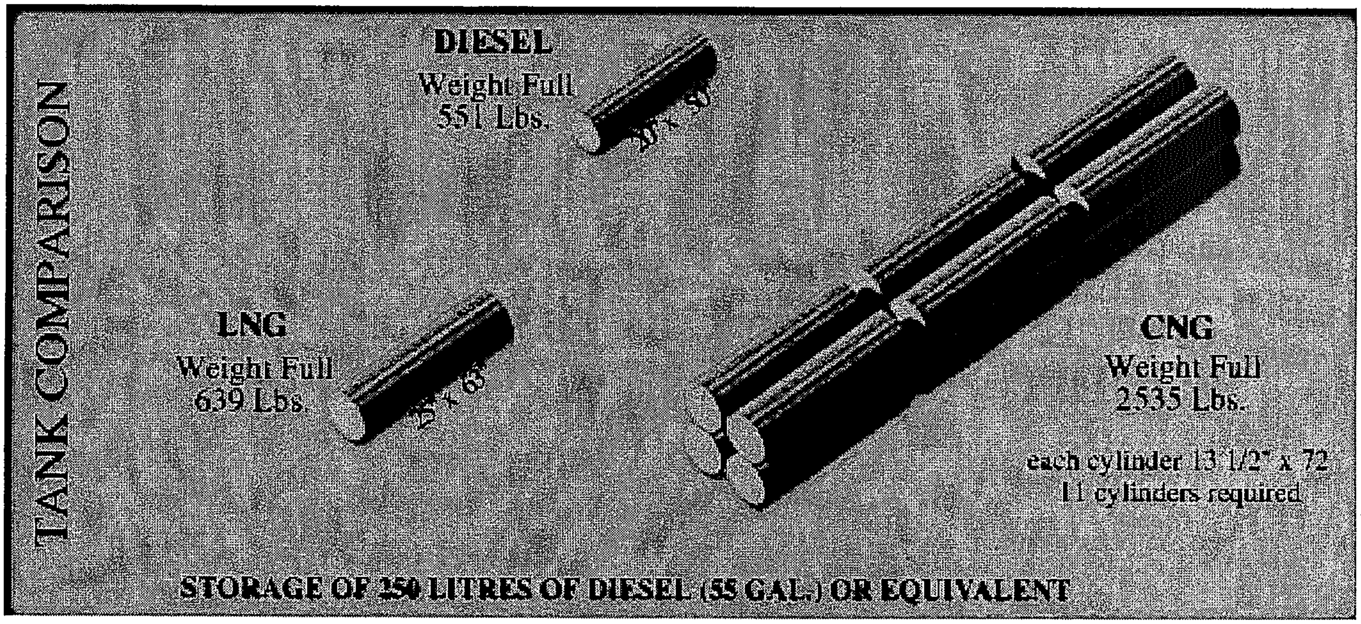
YEAR	MAKE	ENGINE	MILES
1993	International Tractor	N4 Cummins 375hp	350,000
1993	International Tractor	N4 Cummins 375hp	400,000
1992	International Tractor	N4 Cummins 375hp	430,000
1992	International Tractor	N4 Cummins 375hp	245,000
1991	Volvo Autocar Tractor	3406 Cat 375hp	400,000
1994	International Tractor	N4 Cummins 375hp	275,000
1995	International Tractor	N4 Cummins 375hp	220,000
1998	Volvo Tractor	Detroit 60 series 435hp	200,000
1998	Volvo Tractor	Detroit 60 series 435hp	280,000
1998	Volvo Tractor	Detroit 60 series 435hp	179,000
1999	Volvo Tractor	Detroit 60 series 435hp	154,000
1999	Volvo Tractor	Detroit 60 series 435hp	139,000
2000	Volvo Tractor	Detroit 60 series 435hp	192,000
2000	Volvo Tractor	Detroit 60 series 435hp	195,000
2000	Volvo Tractor	Detroit 60 series 435hp	100,000
2000	Volvo Tractor	Detroit 60 series 435hp	130,000
2002	Sterling Tractor	Detroit 60 series 435hp	138,000
2002	Sterling Tractor	Detroit 60 series 435hp	59,000
2002	Sterling Tractor	Detroit 60 series 435hp	118,000
2002	Sterling Tractor	Detroit 60 series 435hp	61,000
2003	Sterling Tractor	Detroit 60 series 435hp	58,000
2003	Sterling Tractor	Detroit 60 series 435hp	79,000
2003	Sterling Tractor	Detroit 60 series 435hp	89,000
2003	Sterling Tractor	Detroit 60 series 435hp	36,000
2004	Western Star Tractor	Detroit 60 series 435hp	20,000
2004	Western Star Tractor	Detroit 60 series 435hp	19,000
2004	Western Star Tractor	Detroit 60 series 435hp	27,000
2004	Western Star Tractor	Detroit 60 series 435hp	23,000
1992	Volvo Loader	6 cyl Volvo	**21,000**
1999	Volvo Loader	6 cyl Volvo	**14,600**
1999	Volvo Loader	6 cyl Volvo	**11,700**
1994	Volvo Loader	6 cyl Volvo	**14,400**
1994	Volvo Loader	6 cyl Volvo	**12,610**
2000	Volvo Loader	6 cyl Volvo	**8,400**
2001	Volvo Loader	6 cyl Volvo	**7,000**
2003	Volvo Loader	6 cyl Volvo	**2,000**
1982	Ford 9000 Dump Truck	855 Cummins	100,000
1982	Ford 9000 Dump Truck	855 Cummins	90,000
1992	Hyster Forklift	4.3 V6 Gas	1400
1991	Kal-Mar Forklift	4 cyl gas	2300
1993	Hyster Forklift	4 cyl gas	800
1991	Chevy Van	V6 gas	100,000
1997	Chevy Truck	V8 gas	100,000
1997	Chevy Truck	V8 gas	100,000
1998	Chevy Truck	V8 gas	100,000
1994	Chevy Truck	V8 gas	80,000
2001	Chevy Truck	V8 gas	90,000
2001	Chevy Truck	V8 gas	80,000
1998	Chevy Truck	V8 gas	95,000
2001	Dodge Truck	V8 gas	70,000

1992	Chevy Truck	V6 gas	100,000
1992	Chevy Truck	V8 gas	90,000
1992	Chevy Truck	V8 gas	95,000
2003	Ford Explorer	V8 gas	10,000
2001	Chevy Van	V6 gas	40,000
1992	Ford Van	V6 gas	95,000
1991	Ford Van	V6 gas	89,000
1999	Ford Van	V8 gas	20,000
1991	Freightliner Rolloff	Detroit 60 series	103,000
1997	International Truck	DT 466 EHT	60,000
1989	Chevy Truck	V8 gas	120,000
1999	Chevy Truck	V8 gas	51,000
2003	Ford Truck	Powerstroke Diesel	11,000
2003	Ford Truck	V8 gas	15,000
2004	Ford Truck	Powerstroke Diesel	5,000
2003	Sterling	Cat-C-12	8,000
2003	Freightliner	Cat-7.2-3126	10,000
2004	Peterbilt	Cat-7.2	19,000
2004	Peterbilt	Cat-7.2	16,000
2002	Komatsu Trackhoe	Isuzo	**5422**
1999	Samsung Trackhoe	Cummins	**8800**
2002	Komatsu Backhoe	Isuzo	**800**
2003	John Deere Tractor	John Deere	**1000**
2003	John Deere Tractor	John Deere	**1000**
2000	Tipper	Cat	**13,000**

Bold Numbers are Hours of Operation

Fuel Tank Comparison (55 gal of diesel or equivalent energy):[3]

Diesel	LNG	CNG
20"x 50"dia. Tank	26"x 63"dia. Tank	Qty 11-13"x 72"dia. Tanks
551 lb.	639 lb.	2535 lb.



Fueling:

LNG fueling can be achieved in a matter of minutes. Most fueling facilities have the capability of 40-60 gpm. Fueling can be done either by pressure transfer or by pump.

CNG fueling can be done at various rates of fills. Most fueling is done at a slow fill due to the cost of the compressor stations. Slow fill is usually done overnight at approximately 10 gph. Fast fill rates can achieve up to 4 gpm.

[3] *Cummins Alternative Fuels, Quick Reference Guide #3605953, March, 1995*