DOE/EE/35034--T1

# Greenhouse Gas Reduction by Recovery and Utilization of Landfill Methane and $CO_2$ Technical and Market Feasibility Study Boului Landfill, Bucharest, Romania

## FINAL REPORT

September 30, 1997 - September 29, 1998


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# Executive Summary

The project is a landfill gas to energy project rated at about 4 megawatts (electric) at startup, increasing to 8 megawatts over time. The project site is Boului Landfill, near Bucharest, Romania. The project improves regional air quality, reduces emission of greenhouse gases, controls and utilizes landfill methane, and supplies electric power to the local grid.

The technical and economic feasibility of pre-treating Boului landfill gas with Acrion's new landfill gas clean-up technology prior to combustion for power production is attractive. Acrion's gas treatment provides several benefits to the currently structured electric generation project: 1) increase energy density of landfill gas from about 500 Btu/ft$^3$ to about 750 Btu/ft$^3$; 2) remove contaminants from landfill gas to prolong engine life and reduce maintenance; 3) recover carbon dioxide from landfill gas for Romanian markets; and 4) reduce emission of greenhouse gases methane and carbon dioxide.

Greenhouse gas emissions reduction attributable to successful implementation of the landfill gas to electric project, with commercial liquid $CO_2$ recovery, is estimated to be 53 million metric tons of $CO_2$ equivalent over its 15-year life.

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# 1. INTRODUCTION

## 1.1 Authority

Contract DE-FG02-97EE35034 was awarded to Acrion Technologies, Inc., on September 30, 1997 by the U.S. Department of Energy in pursuant to Acrion's proposal entitled "Greenhouse Gas Reduction by Recovery & Utilization of Landfill Methane and $CO_2$: Technical and Market Feasibility Study, Boului Landfill, Bucharest, Romania." Acrion's proposal was dated July 23, 1997. Major subcontractors to Acrion were Power Management Corporation (Bellvue, Washington, USA) and Petrodesign, S.A. (Bucharest, Romania).

## 1.2 Scope

Principal work efforts were 1) develop process configurations to remove volatile organic compounds from Boului landfill gas and produce commercial liquid carbon dioxide, such configurations being compatable with the current state of development of the existing Boului landfill gas to electric project, 2) characterize the Romanian market for carbon dioxide and determine potential for selling $CO_2$ produced at Boului landfill, and 3) quantify greenhouse gas emission reduction achieved through implementation of a Boului landfill gas to electric project. The opportunity to produce $CO_2$ at Boului and sell $CO_2$ in Romania appear promising.

## 1.3 Organization

Section 2 reviews the historical and technical background information relevant to the contract work Section 3 discusses work performed under each of the contract tasks, and the results obtained. Section 4 discusses greenhouse gas emissions related to the Boului landfill, and potential reductions achieved through project implementation. Conclusions and recommendations are presented in Section 5.

# 2. BACKGROUND INFORMATION

## 2.1 Historical

Much discussed today is the desire to reduce emissions of suspected greenhouse gases, especially carbon dioxide. Methane is less notorious, although it is a more potent greenhouse gas. Methane can absorb up to 25 times more infrared radiation than carbon dioxide. Methane sources are as varied and geographically diffuse as the digestive systems of termites and ruminants, natural gas processing and transportation systems, coal seam methane, and municipal landfill gas (LFG). Methane released from municipal landfills is believed responsible for about two percent of the total atmospheric greenhouse effect. Methane and carbon dioxide are produced by anaerobic bacterial digestion of the biodegradable portion of municipal solid waste; the quantity and composition of the gas are a function of moisture, pH, and air intrusion among other things.

The composition of typical municipal LFG is shown in Table 1. Landfill gas, in addition to methane, is composed of an almost equal amount of $CO_2$ along with trace volatile organic compounds (VOC's). VOC's contribute to smog and ozone and many are carcinogenic [1].

**TABLE 1**

Range of Gas Composition
Typical of Municipal Landfills

| Component | Mol% (Dry Basis) |
|---|---|
| Methane | 50 - 60 |
| Carbon Dioxide | 35 - 45 |
| Oxygen | 0 - 0.5 |
| Nitrogen | 0 - 2.0 |
| Other Contaminants | 0 - 1.0 |

Landfill gas is a source of recoverable methane and carbon dioxide, and if collected and utilized could displace oil, coal or other gas sources. Vice President Gore has advocated aggressive exploration for new technologies to recover and utilize methane from landfills [2]; this is reflected in the Clinton Administration's promotion of landfill gas-to-energy with three landfill gas initiatives in its Climate Change Action Plan [3]. Estimates of methane vented from existing U.S. landfills approach one *trillion* SCF/year [1], about 5% of domestic natural gas consumption. Worldwide, landfill methane emissions are believed to approach 3.5 *trillion* SCF/year [4]. A representative municipal landfill in a major U.S. city generates between *5 and 10 million* standard cubic feet of LFG per *day* (5 to 10 MMSCFD), enough to supply natural gas for upwards of 3,000 residential dwellings.

The "Boului Project" represents an effort to introduce and apply best available landfill management as practiced in the U.S. to the largest landfill in Romania, the Ochiul Boului Landfill. Development of the Boului Project began in December, 1992, with formation of a partnership, North American World Trade LFG, L.P. (NAWT LFG LP) by the two general partners, Power Management Corporation (PMC, Bellevue, Washington) and North American World Trade Ltd. (NAWT, New York, New York).

Early in 1993, Maguire Group, Inc., agreed to perform as Owner's Engineer and, with assistance from PMC and NAWT, was successful in obtaining a grant from USAID [5] to conduct a landfill gas-to-energy project feasibility study in Romania. Project funding was provided by USAID (50%), PMC (25%), and NAWT (25%). Maguire Group concluded that a power generation project, combusting raw landfill gas to generate electricity, would be economically and technically feasible, and benefit the local environment through better control and management of landfill effluent streams, both liquids and gases.

The City of Bucharest has expressed a desire to buy electric power from the proposed facility and signed a Term Sheet to that Effect. The Romanian Electric Authority (RENEL) is willing to wheel power produced at Boului through its grid to Bucharest.

NAWT LFG LP has prepared a power purchase contract and presented it to the City and RENEL for review. A turnkey contractor has been selected and financing arrangements have been made, subject to signing of applicable contracts. Ownership of the Ochiul Boului Landfill reverted in late 1997 from the City of Bucharest to the City of Popesti-Leordeni by action of the Government of Romania (GOR). Discussions are now in progress with the City of Popesti-Leordeni to obtain landfill site control as required for installation of gas collection infrastructure, management of the well field, and siting of the power plant.

## 2.2 Technical

A major barrier to widespread utilization of landfill gas (LFG) for energy and merchant $CO_2$ is reliable, economic VOC removal. VOC's challenge separation technology several ways: 1) the list of *potential* VOC's contains literally hundreds of chemical compounds, including toxic species such as vinyl chloride and hydrogen sulfide, 2) no two landfills exhibit the same lineup of VOC's, and 3) VOC's change throughout the gas production life of a landfill.

Acrion has developed technology to remove contaminants from LFG with in-situ *cold liquid* carbon dioxide obtained directly from LFG. (The technique uses conditions distant from component extraction with *supercritical* $CO_2$.) A stream of contaminant-free methane and carbon dioxide is produced, along with a concentrated stream of contaminants in carbon dioxide. The intermediate contaminant-free stream is processed to separate $CO_2$ from methane to yield clean methane and liquid $CO_2$. The contaminant laden $CO_2$ stream is thermally oxidized in the landfill flare.

Acrion's liquid $CO_2$ wash technology is unique in several ways: 1) the VOC separating agent, liquid $CO_2$, is obtained directly from raw LFG, eliminating the need to purchase, store and dispose of separating agents such as organic solvents and solid sorbents; 2) cold liquid $CO_2$, a physical solvent with great affinity for VOC's, requires no process modification as VOC composition changes with time; 3) energy invested in LFG compression is preserved during bulk $CO_2$ removal, permitting economic recovery of high pressure liquid $CO_2$; 4) VOC's are concentrated for efficient incineration, reducing NOx and other air emissions; and 5) $CO_2$ wash, based on conventional chemical engineering unit operations, affords low technical risk for production of a variety of fuels and chemicals derived from methane and $CO_2$, depending on local market needs.

# 3. PROGRAM TASK DISCUSSION AND RESULTS

## 3.0 Task 0

## Review Assignment of Team Members Task Responsibilities, Project Schedule, and Milestones.

Team members consisted of Acrion Technologies, Inc. (Acrion, Cleveland, Ohio), prime contractor to the U.S. Department of Energy; Power Management Corporation (PMC, Bellevue, Washington), subcontractor to Acrion; and Petrodesign S.A. (Petrodesign, Bucharest, Romania), consultant to PMC. The responsibility, including tasks and schedule, of each team member was reviewed. The overall Project schedule and schedule milestones were reviewed during early October, 1997.

## 3.1 Task 1

## Review Assumptions, Parameters and Current Process Strategy Proposed for Boului Landfill Gas Recovery

Assumptions, parameters and current landfill gas recovery and utilization strategies developed to date for Boului landfill were reviewed and examined. An electric power project is envisioned based on engine-generator sets fueled with essentially raw landfill gas; planned base load of the fully developed mature project is 8 megawatts (MW) consuming about 4 million standard cubic feet per day (MMSCFD) of landfill gas.

Aside from municipal solid waste deposited at Boului landfill, no infrastructure for a landfill gas project exists; in particular, no gas wells, no passive vents, no gas collection system, no flares, nothing. The major technical assumption to enable this feasibility study is existence of a viable landfill gas stream. Landfill gas flow has been predicted using industry standard models [for example, Tchobanoglous, 6] for gas generation from decomposition of organic waste. These models utilize information such as the amount of solid refuse in place and its residence time, estimates of solid refuse flow to the landfill now and in the future, climate (seasonal temperatures and amount of moisture). Based on the USAID study [5] and more recent work by EMCON [7], the assumed characteristics of Boului landfill gas for this study are shown in Table 2.

**Table 2**

Boului Landfill Gas Characteristics

| |
|---|
| 53% methane ($CH_4$) |
| 44% carbon dioxide ($CO_2$) |
| 1% inert ($N_2$, trace $O_2$) |
| up to 1,000 ppm VOC |
| 2% water, saturated @ 1 atm, 100°F |
| flow = 4 MMSCFD |

## 3.2 Task 2
## Feasibility of $CO_2$ Recovery and Utilization at Boului Landfill

### 3.2.1 Currently Developed Boului Electric Project

The current strategy for recovery and utilization of Boului landfill gas is shown in Figure 1. This process strategy has been found technically and economically feasible by the project developers, Power Management (PMC) and North American World Trade, Ltd. (NAWT), based on a recent study sponsored by USAID [5], and continuing development work by PMC. No attempt is made to remove VOC's or upgrade the energy density of raw LFG (500 Btu/ft$^3$) prior to combustion in the power plant. Increased engine maintenance and shortened engine life due to contact with VOC's and their combustion products are anticipated and factored into project economic models. Nevertheless, the LFG utilization scheme of Figure 1, which generates electricity while converting methane to carbon dioxide, is a good first step toward reducing landfill methane emissions to atmosphere.

### 3.2.2 Proposed Boului Electric Project with $CO_2$ Recovery and Utilization

The proposed Boului electric project with $CO_2$ recovery and utilization is shown in Figure 2. Figure 2 differs from the current project configuration by insertion of Acrion's $CO_2$ wash process and $CO_2$ recovery step between LFG collection and the electric power plant. This simple, non-invasive process modification improves the current project in several ways: 1) engine fuel energy density is increased from 500 to 740 Btu/ft$^3$; 2) volatile organic compounds (VOC's) are removed from engine fuel, reducing engine maintenance and increasing engine life; 3) VOC's are isolated in a small stream for efficient thermal oxidation; and 4) $CO_2$ is recovered for commercial use.

A process design and cost estimate has been prepared for the production of 57 ton per day (TPD) of pure liquid carbon dioxide (0°F, 300 psia) and 2.83 MMSCFD of high pressure contaminant free medium Btu gas (740 Btu) for electricity production with engine-generator sets. The design is based on Acrion's $CO_2$ wash technology, and treats 4 MMSCFD of raw landfill gas feed.

#### 3.2.2.1 Technical Process Description, $CO_2$ Wash

A detailed process flowsheet of Acrion's $CO_2$ wash process, receiving raw LFG and producing medium Btu gas (740 Btu) and commercial liquid $CO_2$, is shown in Figure 3. All stream and equipment identifiers in the following text refer to Figure 3. Process material and energy balances are in Appendix A.

Stream Raw LFG is compressed to 500 psi in three stages of compression with intercooling and water knock-out between stages. Final gas dehydration to a -80°F dew point is with molecular sieves. The dehydrated, compressed landfill gas leaving compressor Comp3 is cooled in exchanger HX1 with cold recycle gas, medium Btu product gas, and contaminant-rich absorber bottoms. Cooled gas enters the bottom of column ABSCO2 where it is contacted with liquid $CO_2$. Liquid $CO_2$ washes VOC's from the gas. At the top of ABSCO2, liquid $CO_2$ is condensed from the upward flowing gas by heat exchange with the methane stripper reboiler, with evaporating VOC enriched $CO_2$, and with pure $CO_2$. Vapor and liquid disengage in a reflux drum. Vapor, enriched in methane, is warmed by heat exchange with condensing pure $CO_2$, expanded to 350 psi to provide cooling, and heat exchanged with compressed feed gas to produce VOC-free medium Btu fuel gas for the engine-generator sets.

**Figure 1**
**Boului LFG to Electric Project**

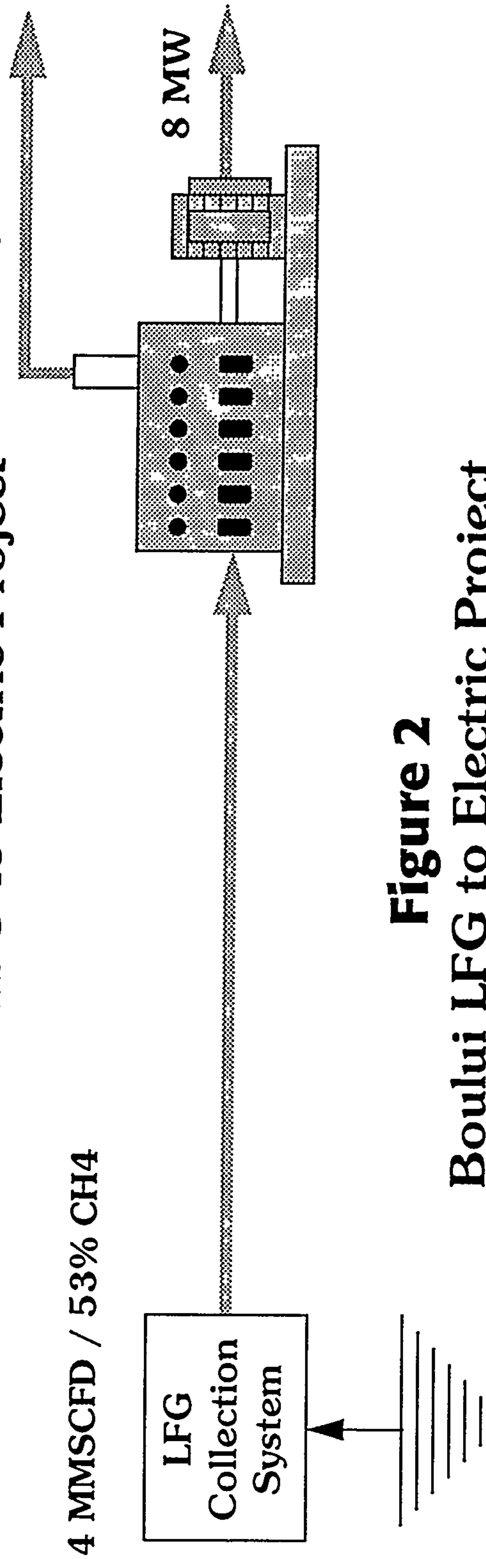



**Figure 2**
**Boului LFG to Electric Project**
**Modified for $CO_2$ Recovery**

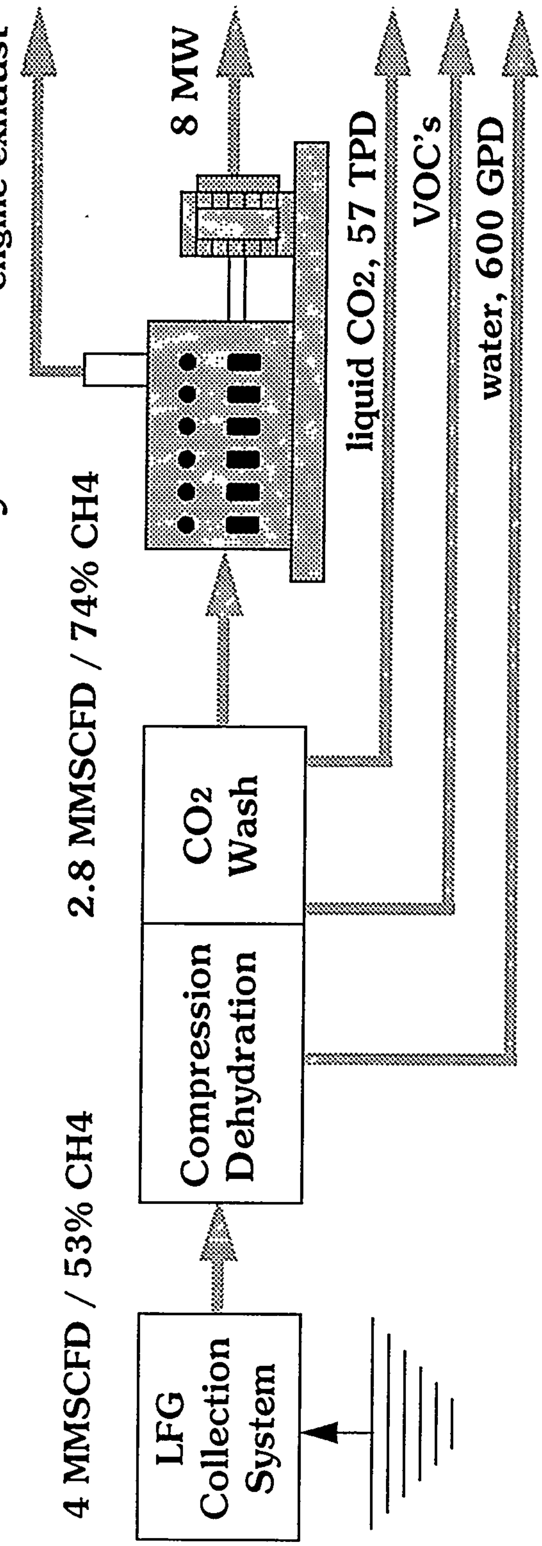
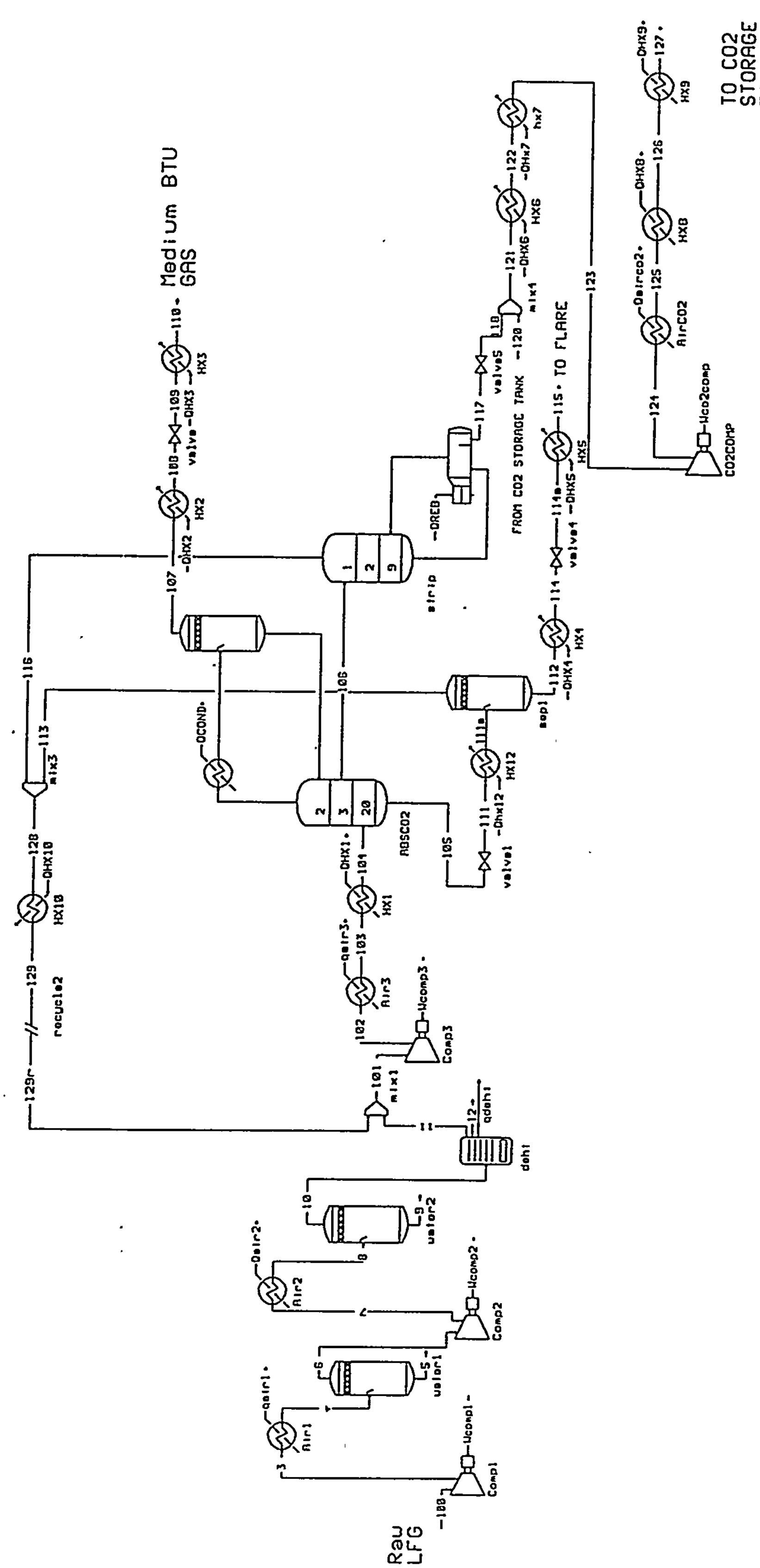


**Figure 3**

LFG to Medium Btu Gas and $CO_2$



Liquid $CO_2$ from the condensation step is pumped (not shown) to the top of absorber ABSCO2. A portion is withdrawn as product; the remainder is refluxed down ABSCO2 to wash VOC's from the upward flowing gas. VOC-enriched $CO_2$ from the bottom of ABSCO2 is flashed to 160 psi and warmed by heat exchange with the condenser to partially vaporize the liquid. This step concentrates VOC's and removes dissolved methane from the liquid. Vapor is recycled and liquid is vaporized by heat exchange with condensing pure $CO_2$ and warmed by heat exchange with the feed. This VOC-enriched gas is thermally oxidized with a small amount of landfill gas to destroy VOC's.

The portion of liquid $CO_2$ taken as product (stream 106) is removed near the top of ABSCO2 and is sent to a methane stripper operating at 180 psi. Dissolved methane and nitrogen are stripped from the liquid with reboiled vapor. Vapor from the top of the stripper (stream 116) is combined with the VOC recycle, warmed by heat exchange with the feed, and recycled to the last stage of feed compression. Pure liquid $CO_2$ from the bottom of the stripper is combined with additional liquid $CO_2$ from product storage, flashed to 78 psi and vaporized by heat exchange with the condenser. This vapor is compressed to 300 psi, and condensed by refrigeration, heat exchange with vaporizing VOC-rich $CO_2$ and cold medium Btu product gas.

#### 3.2.2.2 Preliminary Process Economics, Medium Btu Gas and Liquid $CO_2$

A summary of the preliminary economic evaluation of the proposed modification of the Boului LFG to electric project to recover liquid carbon dioxide is shown in Table 3. Estimated capital cost is $3.4 million including 18% contingency. Annual operating expenses are estimated at $550 thousand. Simple payback period is 3.7 years, infinite-term internal rate-of-return (IRR) is 27%. Price assumed for liquid $CO_2$ is $55 per (short) ton, $60 per metric ton, about 25% of the current delivered liquid $CO_2$ price in Romania (see Section 3.4.1).

Potential credits for greenhouse gas emission reduction play no role in the preliminary economic estimates. An analysis showing the reduction in greenhouse gas emissions that can be achieved is presented in Section 4.

## 3.3 <u>Task 3</u><br>Non-Electric Methane Recovery and Utilization at Boului Landfill

This task was deleted from the Statement of Work during Contract negotiations.

## 3.4 <u>Task 4</u><br>Characterization of Romanian Markets for Carbon Dioxide and Methane

A study of the Romanian market for methane and for carbon dioxide (CO2) was completed. Results of the study are largely positive, as presented below.

### 3.4.1 Carbon Dioxide.

<u>Annual Consumption.</u> About 30,000 metric tons (mt, 2203 lb) of liquid $CO_2$ were manufactured in Romania and sold in 1997. Imports of liquid $CO_2$ in 1997 were about 10,000 mt. The current sales volume of roughly 40,000 mt is expected to increase at 10 to 15% per year.

## Table 3

### Capital, Operating Costs, and Revenues
### Landfill Gas Recovery for Medium Btu Gas and $CO_2$
### (500 psi Absorber)

| | | | |
|---|---|---|---|
| **RAW LFG CONSUMPTION** | | 4.0 MMSCFD | 53% CH4 |
| **OPERATING PARAMETERS** | | | |
| Methane Recovery | | 99.9% | |
| Carbon Dioxide Recovery | | 56.2% | |
| Medium BTU Gas Pressure | | 350 psia | |
| Methane Content of Medium BTU Gas | | 74.3% | |
| Onstream Factor, 350 days/year | | 96% | |
| **PRODUCT** | **PRICE** | | |
| Medium BTU Gas | 0.50 $/MMBTU | | |
| Liquid CO2 | 55$/Ton | | |
| **Power Required** | 791 Kw | | |
| CAPITAL COSTS | | **Installed** | |
| **Equipment** | | **Cost** | |
| Compressors | | 1,192,374 | |
| Refrigerators | | 318,474 | |
| Columns | | 175,510 | |
| Vessels | | 134,596 | |
| Dehydration | | 287,976 | |
| Heat Exchangers | | 462,574 | |
| H2S Removal | | 93,260 | |
| Pumps | | 30,441 | |
| CO2 Storage Tank | | 211,965 | |
| Capital Cost | | 2,907,168 | |
| Contingency (18%) | | 523,000 | |
| **Total Capital Costs** | | **3,430,168** | |
| ANNUAL OPERATING EXPENSES | | | |
| **Electric Power** | 0.027 $/Kw-hr | 179,345 | |
| **SulfaTreat** | | 10,933 | |
| Labor ($12/hr, 2 operators/day) | | 67,000 | |
| Labor Overhead (100% of labor) | | 67,000 | |
| Maintenance Materials (2% of capital) | | 69,000 | |
| Maintenance Labor (3% of capital) | | 103,000 | |
| Taxes & Insurance (1.5% of capital) | | 51,000 | |
| **Total Operating Costs** | | **547,000** | |
| ANNUAL INCOME | **Amount** | **Daily** | **Annual** |
| Medium BTU Gas | 2,832 MSCFD | 1,052 | 368,000 |
| CO2 | 57 TPD | 3,146 | 1,101,000 |
| Total Income | | 4,198 | 1,469,000 |
| PAYBACK PERIOD | 3.72 Years | ACRION TECHNOLOGIES 1-Sep-98 | |

**Sale Price.** The price of liquid $CO_2$ delivered via road tankers is $180 to $260 per mt. The large variation in price is due primarily to transportation costs from the point of manufacture to the point of delivery. The price if delivered in high pressure gas cylinders is $190 to $400 per mt. The price is set by the market, not by the government. For comparison, large U.S. consumers of liquid $CO_2$ generally pay less than $100/ton (short ton, 2000 lb) delivered, while smaller consumers typically pay from $100/ton up to $250/ton or more depending on amount, distance transported, and schedule of consumption. Prices tend to increase in summer, drop in winter.

**Producers/Distributors.** Table 4 shows major producers, their location, recent prices, and method of distribution:

**Table 4**

Major Producers of $CO_2$ in Romania

| *Manufacturer* | *Location* | *$/mt, Delivered* | *Distribution* |
|---|---|---|---|
| BUSE PRODGAZ SRL | Pitesti | 190 | Road tankers |
| Schela Petroliera (oil field) | Ciocaia-Oradea | 200-240 | Road tankers, cylinders |
| AZOMURES | Targu Mures | 250 | Cylinders |
| ARG | Deva | 180-260 | Road tankers, cylinders |
| WESTTIM | Caransebes | 265 | Cylinders |
| Progresui | Ploiesti | 190 | Cylinders |
| Fabrica de Conserve (can factory) | Bailesti-Arges | 380 | Cylinders |
| BIOXID "95" | Braila | 320 | Cylinders |

Three $CO_2$ manufacturers were idle at the time of this study, due to ammonia and fertilizer plant shut downs: AMONIL in Slobozia; DOLJCHIM in Craiova; and SOFERT in Bacau. Plans for re-activation of these plants is unknown at this time. Prolonged or permanent shut-down of these ammonia fertilizer plants would provide further incentive for $CO_2$ recovery from landfill gas.

Transportation charges for liquid $CO_2$ delivered by road tanker are 3¢ to 5¢/mt/km (kilometer). Thus, as in the United States, transportation is a significant part of the delivered cost of liquid $CO_2$. Production and distribution of $CO_2$ from Boului landfill would benefit being geographically near the Bucharest market.

Sales of liquid $CO_2$ are made direct (manufacturer to end user) or through a distributor. Major distributors of liquid (and solid) $CO_2$ in Romania include:

1. SILION SRL
2. MAVIS SRL
3. NECULA SRL
4. JULVINT SRL, and
5. MICROPROD SRL

Purchasers/Consumers of $CO_2$.. The principal purchasers/consumers of liquid $CO_2$ in Romania include:

1. SIDEX (Galati, Romania) in Galati
2. Energoreparatia (Bucharest, Romania)
3. GRIVITA INT. (Bucharest, Romania)
4. TUBORG (Bucharest, Romania)
5. Coca Cola (Bucharest and Ploiesti, Romania)
6. Ape Minerale (Biborteni, Romania)
7. TEC (Bucharest, Romania)

Process Sources of $CO_2$. Carbon dioxide for the Romanian market is obtained at present from the following sources:

1. Alcohol fermentation,
2. Combustion of liquid, solid or gaseous carbonaceous fuels,
3. Ammonia waste gas.

Uses of $CO_2$. The principal uses of $CO_2$ in Romania food freezing, beverage carbonation, and industrial processes including welding, synthesis chemistry, and casting.

$CO_2$ Specifications. Liquid $CO_2$ specifications are shown in the following table. These specifications do not include $CO_2$ used for pharmaceutical purposes. Type "A" is used by the food industry. Type "S" is used for welding and synthesis chemistry. Type "T" is used in foundries for metals casting. Type "T" is specified at two quality levels; Type "T1" and Type "T2," depending upon the application.

The existence of several grades of commercial liquid $CO_2$ in Romania may be due to several factors, both favorable to the production of liquid $CO_2$ from Boului landfill gas with Acrion's $CO_2$ wash technology: 1) much of the commercial $CO_2$ in Romania may be consumed in non-food industries less resistant to purchase $CO_2$ produced from landfill gas (this could be very helpful in overcoming the negative "garbage" image of landfill $CO_2$ constantly trotted out by market and sales people in the United States), and 2) up-grade of $CO_2$ from available Romanian sources may be relatively expensive, limiting $CO_2$ purity to "two 9's," i.e., type S at 99.5% $CO_2$. Acrion's $CO_2$ wash economically produces "four 9's or better," i.e., 99.99% $CO_2$, and easily meets not only the existing specifications for $CO_2$ in Romania, but also for domestic "food-grade" $CO_2$, essentially the only grade widely distributed in the United States.

**Table 5**

CO2 Specifications for Romanian Markets

| Characteristic | Grade of CO2 | | | |
|---|---|---|---|---|
| | A | S | T1 | T2 |
| Color | Colorless | - | - | - |
| Smell | No smell | - | - | - |
| Taste | Slightly pungent, no foreign taste | - | - | - |
| CO2 % by Volume | 98 | 99.5 | 98 | 96 |
| Humidity, $g/m^3$ max. | 2 | 0.3 | - | 3 |
| Dew Point, $^{o}C$, max. | - | -30 | - | - |
| Carbon Monoxide | nil | - | - | - |
| Mineral Oil | nil | - | - | - |
| Hydrogen Sulfide | nil | - | - | - |
| Redox Substances*, $mg/m^3$ max. | 30 | - | - | - |
| Vanadium** | nil | - | - | - |
| Aromatic Hydrocarbon*** | nil | - | - | - |

NOTES:

*Nitric acid, sulfuric acid, alcohols, esters, aldehydes, organic acids, diethanolamine, monoethanolamine.

**Vanadium applies only for CO2 produced from ammonia waste gases.

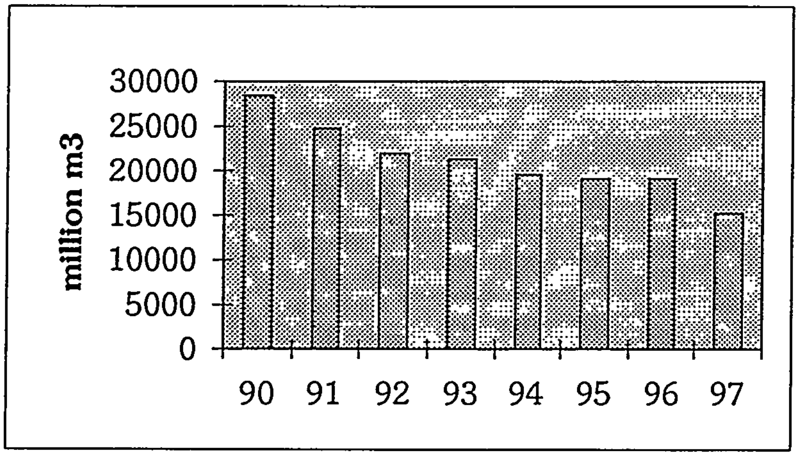
***Aromatic hydrocarbon applies only for CO2 produced by combusting carbonaceous fuels.

### 3.4.2 Methane.

Annual Production. Domestic production of natural gas is shown in Figure 4. Domestic production has decreased, on average, about 8% per year since 1990, from 28,336 million $m^3$ (cubic meter) in 1990 to 15,203 million $m^3$ in 1997. Approximately 92.5% of the natural gas is methane, the balance consisting principally of ethane, propane and other hydrocarbon gases.

## Figure 4

Romanian Domestic Natural Gas Production
(million of cubic meters per year)




Sales. The annual volume of sales for 1997 totaled 20,014 million $m^3$, of which 15,203 million m3 (76%) was produced in Romania, 4,811 million $m^3$ (24%) was imported. Because of current slowing of general industrial activity in Romania, gas sales are expected to remain static or decline modestly over the next several years. For comparison, the quantity of recoverable methane from Boului landfill is estimated at 21 million $m^3$ per year, about 0.5% of Romania's natural gas imports in 1997. Recovery of methane at several landfills in Romania could displace up to 2% of Romania's current natural gas imports.

Supply, Distribution. The major suppliers of natural gas in Romania are:

1. ROMGAZ (wholly owned by Romania government)
2. PETROM (ownership uncertain)
3. WIROM (owned by ROMGAZ and Wintershall)
4. GAZPROM (wholly owned by Russian government)

ROMGAZ owns all pipelines in Romania and thus is the sole distributor of natural gas.

Price. Sale price as of March 1, 1998:

- To industrial users - \$95.00 per 1,000 $m^3$ = \$2.69 per mmBtu (million Btu)
- To residential users - \$50.00 per 1,000 $m^3$ = \$1.42 per mmBtu

Natural gas prices are established and controlled by the Government of Romania (GOR). Sales price is the same for domestic gas and imported gas. For comparison, domestic U.S. residential natural gas consumers supplied by Consolidated Natural Gas Company (Pittsburgh), a large domestic gas utility serving Ohio, Pennsylvania, and West Virginia, pay about \$6.50 per mmBtu (\$230 per 1,000 $m^3$, August, 1998); industrial customers in the U.S. typically pay less, just the flip of Romania.

2. Chemical industry
3. Petroleum processing
4. Metallurgy
5. Metal products

Natural Gas Availability. Natural gas is in short supply in Romania, and is expected to remain so until new trans-national pipelines are built and more natural gas is imported from Russia. Gas pressure in both main lines and distribution lines fluctuates and drops to extremely low levels from time to time due to demand exceeding supply.

Other Landfills. As a part of Task 4, a preliminary review was made of other landfills which might be suitable for development of landfill gas recovery projects based on Acrion's $CO_2$ wash technology for contaminant management. Four major cities in Romania were surveyed. Data collected is shown in Table 6.

**Table 6**

Large Romanian Landfills

| City /Landfill | Size (hectares) | Volume of MSW in place (cubic meters) | Date Opened/Date Scheduled to Close | VOLUME of MSW Deposited Yearly (cubic meters) |
|---|---|---|---|---|
| Ploiesti | 15 | 3,450,000 | 1948/ Open | 394,622 |
| Craiova - Valea Sarpelui Craiova | 16 | 3,360,000 | 1980/2002 | 80,000 |
| Craiova - Mofleni | 19 | 4,850,000 | 1978/2003 | 180,000 |
| Sibiu | 20 | 3,000,000 | 1975/2003 | 98,000 |
| Medias | 3.5 | 1,600,000 | 1968/2025 | 66,000 |

## 3.5 Task 5
## Configure Boului Landfill Gas/Electricity Generation Project to Incorporate Add-On $CO_2$ Recovery

Optional Configurations. Based on the results of Task 2, several configuration options utilizing Acrion's $CO_2$ wash technology appear economically feasible for the Boului Project. Two optional configurations are presented below which fit within the currently planned Boului Project; the third option considers the alternative of producing methane for pipeline distribution rather than combusting methane on-site to generate electricity.

### 3.5.1 Configuration 1, Options for Currently Planned Boului Project

The first option is to construct the Boului Gas-to-Electric Energy Project substantially as planned. The major task elements under this first option include:

- Modify landfill management practices to conform to current environmental practice.
- Install landfill gas collection and flare system.
- Install service pipeline from the main natural gas pipeline surrounding Bucharest to the Boului Landfill to provide backup fuel to the power plant.
- Construct a gas-to-electric energy facility (the "Power Plant") at the Boului Landfill, with electric transmission lines from the facility to a nearby electrical substation.

The second option is to install an Acrion $CO_2$ wash system (the "Separation Facility") at the Boului Landfill between the landfill gas collection system and the Power Plant. The Separation Facility separate s collected landfill gas into three streams:

1) Clean, medium to high Btu gas at pressure (approximately 300 psia minimum, 740 Btu per $ft^3$ or greater) consisting only of methane and $CO_2$, free of volatile organic compounds (contaminants);
2) Clean, liquid $CO_2$ at 0°F and 300 psia;
3) Carbon dioxide (about 99%) containing all volatile organic compounds removed from the landfill gas and some methane (about 0.5%).

The fate of these three streams is as follows:

1. Stream 1) is combusted in the Power Plant to generate electricity.
2. Stream 2) is sold as commercial high-purity liquid $CO_2$.
3. Stream 3) is thermally oxidized at the landfill flare to destroy volatile organic compounds.

### 3.5.2 Configuration 2, Produce Pipeline Methane and $CO_2$ at Boului

This option considers installation of Acrion's $CO_2$ wash Separation Facility to enable production of pipeline quality methane from Boului landfill gas. In addition to pipeline methane, upwards of 85 to 90% of the $CO_2$ in the landfill gas is recoverable as commercial liquid $CO_2$. No gas-to-electric project would be built. The major task elements under this option include:

- Modify landfill management practices to conform to current environmental practice.
- Install a landfill gas collection and flare system.
- Install service pipeline from the main natural gas pipeline surrounding Bucharest to the Boului Landfill to receive produced methane.
- Install an Acrion gas separation facility (the "Separation Facility") at the Boului Landfill.

The Separation Facility separates the collected landfill gas into three streams:

1) Clean, high Btu gas (>950 Btu/ft$^3$; contaminant-free and substantially all methane.
2) Clean, liquid $CO_2$ at 0°F and 300 psia.
3) Carbon dioxide (about 98%) containing all volatile organic compounds removed from the landfill gas and some methane (about 0.5%).

The fate of these three streams is as follows:

1. Stream 1) will be sold to one of the natural gas providers or to an industrial user and will be injected into the main distribution pipeline or piped direct to a user.
2. Stream 2) is sold as high purity commercial liquid $CO_2$.
3. Stream 3) is thermally oxidized at the landfill flare to destroy volatile organic compounds.

### 3.5.3 Technical Issues.

LFG-to-Energy. The presently planned configuration (without the use of Acrion's $CO_2$ wash gas separation technology) uses commercially proven technology throughout. The system consists of 1) a gas collection system, 2) a cleaning and compression system suitable for the engines selected, 3) reciprocating internal combustion engines coupled to generators, 4) an electrical control system, and 5) electrical transmission lines connecting the electric power from the generators to the electrical grid. This basic configuration has been used on hundreds of landfills in the United States and Western Europe.

Acrion $CO_2$ Wash Gas Separation Technology. $CO_2$ wash technology has been demonstrated extensively with simulated landfill gas in Acrion's Cleveland shop, and is now undergoing tests and demonstrations with raw landfill gas at the Al Turi Landfill, Goshen, New York, USA. The pilot plant processes 70 SCFM of raw landfill gas into a clean gas (70% methane, 30% carbon dioxide) and a carbon dioxide stream containing separated volatile organic compounds. The purpose of operation at Al Turi Landfill is to demonstrate high level removal of volatile organic compounds from raw landfill gas; no methane or $CO_2$ is produced for commercial purposes.

Results obtained from the demonstration unit during summer 1998 show volatile organic compounds being removed to virtually undetectable levels (total contamination of product gas below 500 ppb). Negotiations are underway for commercial landfill gas recovery projects based on Acrion's technology in the United States.

### 3.5.4 Business Issues.

LFG-to-Energy. The Boului LFG-to-Energy Project was determined to be feasible pursuant to a recent USAID-sponsored study [5]. The Project has since been refined and as now constituted appears economically viable and financeable through sources identified by the developer, North American World Trade LFG, L.P. ("NAWT LP"). NAWT LP is a limited partnership in which PMC and North American World Trade, Ltd. ("NAWT") each owns a 40% general partnership interest. The Project has been discussed extensively by its developer with both the City of Bucharest and RENEL. The City has approved a set of Term Sheets which defines the price at which power will be sold by NAWT LP to the City, and provides for NAWT LP site control of the Boului Landfill for purposes of collecting and using landfill gas to generate electric power. The City has reaffirmed its interest in purchasing electric power from the Boului Project in a letter dated March 23, 1998. A draft power purchase agreement has been circulated to the City and RENEL and comments have been received from RENEL.

Since the Term Sheets were signed, ownership of the Boului Landfill has been transferred to the City of Popesti-Leordeni and the issue of site control for the purposes of the Boului Project has not yet been resolved.

Pursuant to a request by PMC, the environmental firm EMCON, Inc. prepared a proposal to improve operating practices at the Boului Landfill which would eliminate a number of existing environmental problems and would extend landfill life by some 20 years. Both features are of great importance to the region.

The major business risk is the uncertain LFG supply. LFG-to-energy projects sited at landfills utilizing latest landfill gas management technology are still subject to significant variations in LFG supply, due to the many variables in landfill gas generation. Boului Landfill does not practice landfill gas management technology and until such technology is adopted, LFG supply will be highly uncertain. As a consequence, a condition precedent for proceeding with the Project is an alternate source of fuel (natural gas from the nearby pipeline).

Gas Separation. A gas separation facility, either as an adjunct to a gas-to-electrical energy facility or on a stand-alone basis, appears to be feasible based upon laboratory test data and preliminary economic evaluations. This will be supplemented in the near future by data from pilot plant tests. There would be significant business risk in proceeding to install a production facility until demonstration tests of the pilot plant are completed. These tests are scheduled for completion in September, 1998.

## 3.6 TASK 6
## Prepare Proposal Outline for Project Submission to USIJI

An outline of a proposal to be submitted for USIJI review, comments and ultimate approval is presented in Appendix B.

## 3.7 Task 7
## Preparation of Grant Final Report

Task completed with the submittal of this Final Report, September, 1998.

# 4. DISCUSSION OF GREENHOUSE GAS EMISSIONS AND SEQUESTRATION

## 4.1 Historic Estimate

Gas is generated within the Boului landfill by the anerobic bacterial decomposition of organic material. This gas migrates through the buried waste and freely enters the atmosphere. Today, no gas collection system exists at Boului; all gas generated enters the atmosphere.

Estimates of landfill gas generation at Boului have been made based on the amount of organic solid waste landfilled [5]. For the past five years, 1994 through 1998, the average landfill gas generation rate is predicted to have been 3,400 standard cubic feet per minute (SCFM), **4.9 million SCF/day,** 1.8 billion SCF/year.

The historical greenhouse gas contribution to the atmosphere from Boului landfill can be determined from the above estimated landfill gas generation rate and the landfill gas composition shown below. (The gas composition in Table 7 differs slightly from the composition assumed for process engineering studies (Table 2); 55% methane vs 53%, 40% $CO_2$ vs 44%. The difference has no impact of the conclusions drawn here regarding greenhouse gas emissions, and emission reductions attainable through project implementation.)

**Table 7**
**Boului Landfill Gas**

| Component | Concentration | mt/MMSCF |
|---|---|---|
| methane, $CH_4$ | 55% | 10.5 |
| carbon dioxide, $CO_2$ | 40% | 21.1 |
| inerts ($N_2$, $O_2$) | 5% | |
| contaminants | 1,000 ppm | |

mt/MMSCF = metric ton per million standard cubic feet

example for methane:

$$\frac{(55\%)(1 \text{ million ft3})(16 \text{ \#/mole})}{(379 \text{ ft3/mole})(2204.6 \text{ \#/mt})} = 10.5 \text{ mt}$$

Three components of landfill gas are greenhouse gases; in order of increasing greenhouse effect (per molecule) they are: carbon dioxide, methane, and chloroflurocarbon (CFC) compounds present in the contaminants. The principal CFC compounds in landfill gas are trichlorofluoro-methane, dichlorodifluoromethane, and chlorodifluoromethane; these compounds are refrigerants commonly known as R-11, R-12, and R-22, respectively.

Methane and CFC's are better infrared absorbers and have longer average residence times in the atmosphere than $CO_2$. The contribution of methane and trace CFC's to the greenhouse effect, in terms of equivalent $CO_2$ emissions which would cause the same atmospheric heat retention, can be estimated with the aid of a GHG emissions index [Ellington, 8]. The index was developed to help evaluate mitigation strategies involving emissions of a variety of greenhouse gases by relating these emissions to an equivalent amount of $CO_2$. For example, Ellington derives a *mass factor* of 144 for methane, meaning release of 1 mt methane induces atmospheric heat retention equivalent to release of 144 mt $CO_2$.

**Table 8**

**Greenhouse Gas Emissions from Boului Landfill**
**Conversion to Equivalent Metric Tons of Carbon Dioxide**
**BASIS: 1 million SCFD Landfill Gas**

| | | | |
|---|---|---|---|
| | 1 million SCFD landfill gas = | 2,639 mole | |
| 55% | methane | 1,451 mole CH4 | 10.5 mt CH4 |
| 40% | carbon dioxide | 1,055 mole CO2 | 21.1 mt CO2 |
| 5% | inert | | |

| Compound | MW | Mass Factor [8] | Conc ppm | lb per Basis | mt CO2 Equiv |
|---|---|---|---|---|---|
| CH4 | 16 | 144 | | | 1,517 |
| CO2 | 44 | 1 | | | 21 |
| R-11 | 137 | 104,115 | 2 | 0.72 | 34 |
| R-12 | 121 | 258,000 | 14 | 4.47 | 523 |
| R-22 | 86 | 18,800 | 7 | 1.60 | 14 |
| | | Equivalent Metric Tons of CO2 per Basis: | | | **2,108** |

The historic GHG emissions from Boului are calculated from results presented in Table 8.

$$(2{,}108 \text{ mt/MMSCFD})(4.9 \text{ MMSCFD})(365 \text{ d/yr}) = 3.77 \text{ MM mt CO2 equiv/yr}$$

Thus, the annual historic emission of greenhouse gases at Boului Landfill, *expressed as equivalent tons of* $CO_2$, is 3.77 ***million*** metric ton $CO_2$.

## 4.2 Reference Case GHG Emissions Estimate:

The time period of the project is 15 years, beginning 1999 through the year 2013. This time period is broken into three 5-year segments for purpose of estimating reference case

- GHG emissions. Annual estimates derived with the predictive model developed for landfill gas generation at Boului [5] are averaged over each of the three 5-year periods. Results are shown in Table 9.

**Table 9**

Historic Case and Reference Case
Greenhouse Gas Emissions
Million Metric Ton $CO_2$ Equivalent

| Period | Daily LFG Rate million SCF | Annual GHG Emissions million mt $CO_2$ equivalent |
|---|---|---|
| *Historical Case* | | |
| pre 1999 | 4.9 | 3.77 |
| *Reference Case* | | |
| 1999-2003 | 5.0 | 3.85 |
| 2004-2008 | 5.2 | 4.00 |
| 2009-2013 | 3.6 | 2.77 |

## 4.3 GHG Emissions Estimate with Project:

Project implementation requires two major tasks: 1) design and construction of a gas collection system at Boului landfill, including a landfill gas flare; and 2) installation of a 8 megawatt (mW) electric generation plant fueled with a portion of the collected landfill gas. The gas collection system would not be installed but for the economic return provided by electric power sales.

GHG emissions reductions are achieved by the project in three ways. First, with completion of a gas collection system, flare, and 8 mW power plant, collected landfill methane and contaminants are thermally oxidized (combusted) to primarily $CO_2$ and water. The large greenhouse effect of methane and refrigerant contaminants is destroyed by their conversion to $CO_2$. Each mole of methane combusted produces one mole of $CO_2$. From Table 8, each million SCF of flared landfill gas produces (1,451 + 1,055) = 2,506 mole $CO_2$. The $CO_2$ contribution of combusted refrigerant contaminants is negligible. Thus, one million SCF of combusted landfill gas produces

$$(2{,}506 \text{ mole})(44\#/\text{mole})/(2{,}204.6\#/\text{mt}) = 50 \text{ mt } CO_2$$

The reduction in GHG emissions achieved by collection and combustion of landfill gas for power production, rather than passive venting of landfill gas, is impressive:

$$2{,}100 - 50 = 2{,}050 \text{ mt } CO_2 \text{ equivalent per million SCF of landfill gas}$$

A second GHG emission reduction is achieved by the generation of electric power from landfill methane. The project generates 8 mW electric power from methane combustion, and thus displaces 8 mW of electric power from coal combustion, i.e., indirect fuel switching. Methane combustion produces less $CO_2$ than coal combustion per unit of power produced. Tables 10 and 11 develop $CO_2$ emissions per megawatt of power production from coal and methane combustion, respectively. The reduction in GHG emissions achieved by electric generation from methane rather than coal is:

**12,142 - 5,572 = 6,570 mt $CO_2$ / year / mW**

**(8 mW) (6,750) = 52,560 mt $CO_2$ / year**

The third GHG emission reduction is achieved by recovery and commercial utilization of $CO_2$ from raw landfill gas. Initial Romanian $CO_2$ market studies, coupled with preliminary $CO_2$ recovery process designs based on Acrion's contaminant removal technology, are encouraging. Process designs establish the technical feasibility of $CO_2$ recovery, while $CO_2$ price levels indicate that 55% recovery of $CO_2$ from Boului landfill gas is economically attractive. GHG emission reductions accrue because landfill $CO_2$ is biomass $CO_2$, as opposed to fossil $CO_2$ now serving Romanian markets. Fossil $CO_2$ is produced primarily from natural $CO_2$ wells and by fossil fuel combustion expressly for the purpose of $CO_2$ production. The reduction in GHG emissions achieved by $CO_2$ recovery from raw LFG is estimated as:

**$CO_2$ recovery per million SCF of raw LFG: 0.55 x 21.1 mt = 11.6 mt**

Commercial grade liquid $CO_2$ is recovered by pretreatment of landfill gas combusted as engine fuel; the amount of engine fuel is about 0.5 MMSCFD per megawatt, or 4 MMSCFD for the 8 mW power plant. Thus, $CO_2$ recovery and attendant GHG reduction is estimated at

**(11.6 mt/MMSCFD) (4 MMSCFD) (365 d/y) = 17,000 mt $CO_2$ / year**

Table 12 summarizes GHG emission estimates for the historic, reference and project cases. The project case is reported by GHG reduction activity: 1) landfill gas collected and combusted for power production, 2) fuel switching from coal to methane for 8 mW of electricity, and 3) 55% recovery of $CO_2$ from 4 million SCFD of landfill gas engine fuel prior to combustion.

Table 13 summarizes reductions in GHG emissions attributable to the project. The project generates 8 megawatt electric for 15 years. GHG emission reduction is estimated to be about 53 million metric tons $CO_2$ equivalent over the 15-year life. Large GHG emission reductions will continue beyond the useful electric generation life of the project due to continued operation of the gas collection system and landfill gas flare. The economic feasibility of continued, perhaps expanded, electric generation beyond 15 years is dependent on extension of Boului landfill's current closure date, 2000, and/or revised projections of gas flow made during the project's life. EMCON, an internationally recognized company providing full service capability for the solid waste industry, completed a preliminary study of the Boului landfill for Power Management in October 1997 [7]. EMCON concluded that expansion and continued operation of the Boului landfill through 2020 is feasible, and would help Romania satisfy European Union's general requirements for disposal sites. Thus, prospects for continued operation and increased landfill gas availability at Boului are good. However, NO credit is taken for probable GHG emission reductions realized by continued landfill gas collection and possible continuation and expansion of electric generation beyond the 15-year life of the currently defined electric project.

**Table 10**

**$CO_2$ Production from Coal Combustion per Megawatt of Electric Power**

| | | |
|---|---|---|
| Heat Rate: 1 kW = | 3,412 | Btu/hr |
| @31% efficient, 1 kWe requires | 11,007 | Btu/hr |
| Thermal energy per megawatt electric | 11,007,491 | Btu/hr |
| Coal combustion ΔHc | 13,000 | Btu/lbmass (ash free) |
| Coal molecular weight CH.2 | 12.2 | lbmass/#mole |
| Mole balance | 1 | #mole CO2/#mole "coal" |
| Coal (organic) consumption | @158,600 | Btu/#mole "coal" |
| | 69 | #mole "coal"/hr |
| One megawatt electric produces | 69 | #mole CO2/hr |
| | 1.4 | mt CO2/hr |
| | 33 | mt CO2/day |
| | 12,142 | mt CO2/year |

**Table 11**

**$CO_2$ Production from Methane Combustion per Megawatt of Electric Power**

| | | |
|---|---|---|
| Heat Rate: 1 kW = | 3,412 | Btu/hr |
| @31% efficient, 1 kWe requires | 11,007 | Btu/hr |
| Thermal energy per megawatt electric | 11,007,491 | Btu/hr |
| Methane Combustion ΔHc (lower) | 21,600 | Btu/lbmass |
| Methane molecular weight CH4 | 16 | lbmass/#mole |
| Mole balance | 1 | #mole CO2/#mole CH4 |
| Methane consumption | @345,600 | Btu/#mole CH4 |
| | 32 | #mole CH4/hr |
| One megawatt electric produces | 32 | #mole CO2/hr |
| | 0.6 | mt CO2/hr |
| | 15.3 | mt CO2/day |
| | 5,572 | mt CO2/year |

**Table 12**

Summary
Boului Landfill GHG Emissions Estimate
Historic, Reference And Project Cases

| Period | LFG Flow MMSCF/day | Equivalent $CO_2$ Emissions mt/MMSCF | mt/year |
|---|---|---|---|
| *HISTORIC CASE* | | | |
| 1994 - 1998 | 4.9 | 2,100 | 3.77 million |
| *REFERENCE CASE* | | | |
| 1999-2003 | 5.0 | 2,100 | 3.85 million |
| 2004-2008 | 5.2 | 2,100 | 4.00 million |
| 2009-2013 | 3.6 | 2,100 | 2.77 million |
| *PROJECT (by Activity)* | | | |
| 1) Landfill Gas Collected and Combusted for Power | | | |
| 1999-2003 | 5.0 | 50 | 91,300 |
| 2004-2008 | 5.2 | 50 | 94,900 |
| 2009-2013 | 3.6 | 50 | 65,700 |
| 2) Indirect Fuel Switch, Methane Replaces Coal | | | |
| 1999-2013 | | | (52,600) |
| 3) $CO_2$ Recovery and Utilization | | | |
| 1999-2103 | | | (17,000) |
| *PROJECT TOTAL* | | | |
| 1999-2003 | 5.0 | | 21,700 |
| 2004-2008 | 5.2 | | 25,300 |
| 2009-2013 | 3.6 | | essentially zero |

mt [=] metric ton
MMSCF [=] million standard cubic feet

**Table 13**
Summary
Annual GHG Emissions Estimate
Metric Ton $CO_2$ Equivalent/Year (1,000's)

| Year | ESTIMATED EMISSIONS | | ESTIMATED EMISSIONS REDUCTION | | | |
|---|---|---|---|---|---|---|
| | w/o project | w project | w project | | | |
| | | (electric) | (electric) | (fuel switch) | ($CO_2$) | Total |
| 1999 | 3,850 | 91 | 3,759 | 53 | 17 | 3,828 |
| 2000 | 3,850 | 91 | 3,759 | 53 | 17 | 3,828 |
| 2001 | 3,850 | 91 | 3,759 | 53 | 17 | 3,828 |
| 2002 | 3,850 | 91 | 3,759 | 53 | 17 | 3,828 |
| 2003 | 3,850 | 91 | 3,759 | 53 | 17 | 3,828 |
| 2004 | 4,000 | 95 | 3,905 | 53 | 17 | 3,975 |
| 2005 | 4,000 | 95 | 3,905 | 53 | 17 | 3,975 |
| 2006 | 4,000 | 95 | 3,905 | 53 | 17 | 3,975 |
| 2007 | 4,000 | 95 | 3,905 | 53 | 17 | 3,975 |
| 2008 | 4,000 | 95 | 3,905 | 53 | 17 | 3,975 |
| 2009 | 2,770 | 66 | 2,704 | 53 | 17 | 2,774 |
| 2010 | 2,770 | 66 | 2,704 | 53 | 17 | 2,774 |
| 2011 | 2,770 | 66 | 2,704 | 53 | 17 | 2,774 |
| 2012 | 2,770 | 66 | 2,704 | 53 | 17 | 2,774 |
| 2013 | 2,770 | 66 | 2,704 | 53 | 17 | 2,774 |
| | 53,100 | 1,260 | 51,841 | 789 | 255 | 52,885 |

Total Estimated Reduction in GHG Emissions
Due to Project: *52.9 Million* mt CO2 Equivalent

NOTES:
Column 1) calendar year
Column 2) estimated emissions without project
Column 3) estimated emissions with project implementation
Column 4) estimated emissions *reduction*, column 2) - column 3)
Column 5) estimated ancillary emissions reduction, methane for coal fuel switch
Column 6) estimated ancillary emissions reduction, LFG CO2 recovery
Column 7) total estimated emissions reduction

# 5. CONCLUSIONS

1. Recovery and utilization of Boului landfill gas to generate electric power is technically feasible and economic. Recovery of commercial liquid carbon dioxide using Acrion's $CO_2$ wash technology, without significant modification of the currently planned electric power plant project, also is technically feasible and economic. Implementation of the project, with or without commercial liquid $CO_2$ production, results in significant emissions reduction of greenhouse gases.
2. Officials in the Government of Romania express support for such a project, and are cooperating with PMC to bring closure to the project development phase.

# 6. RECOMMENDATIONS

1. Acrion Technologies, Inc., in partnership with Power Management Corporation and Petrodesign S.A., should submit a proposal for IJI sponsorship which would lead to the construction of a Greenhouse Gas Reduction (GGR) Facility at the Boului Landfill, Bucharest, Romania.
2. Other landfills in Romania should be investigated for application of Acrion's $CO_2$ wash technology to recover commercially significant quantities of methane and carbon dioxide. Romania's domestic supply of natural gas would be enhanced, new technologies and markets based on liquid $CO_2$ could be developed, and greenhouse gas emissions reduced at the same time.
3. As recommended for Romania, landfills in Central and Eastern Europe and the Newly Independent States of the former Soviet Union should be investigated for potential application of Acrion's $CO_2$ wash technology to recover commercially significant quantities of methane and carbon dioxide. Similar benefits would accrue.

# 7. REFERENCES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# APPENDIX A

Material and Energy Balance

Medium Btu Gas and Liquid Carbon Dioxide
Raw Landfill Gas Flow = 4 million SCF/day

Boului Landfill
Bucharest, Romania

Hyprotech's Process Simulator HYSIM - Licensed to Acrion Technologies Inc
Date 98/9/01 Version 386|C2.12 Case Name BOULI2.SIM
Time 10:24:15 Prop Pkg PRSV

LFG to Medium BTU Gas and Liquid CO2 Material Balance

| Stream | | 100 | 110 | 115 | 117 |
|---|---|---|---|---|---|
| Description | | LFG Feed | MediumBTUGas | Flare Gas | CO2 |
| Vapour frac. | | 1.0000 | 1.0000 | 1.0000 | 0.0000 |
| Temperature | F | 70.0000* | 85.0000* | 85.0000* | -29.1241 |
| Pressure | psia | 14.7000* | 350.0000* | 20.0000 | 180.0000 |
| Molar Flow | MMSCFD | 4.0000* | 2.8322 | 0.0793 | 0.9865 |
| Methane | mole frac. | 0.5262* | 0.7431 | 0.0043 | 0.0000 |
| Nitrogen | mole frac. | 0.0097* | 0.0138 | 0.0000 | 0.0000 |
| CO2 | mole frac. | 0.4385* | 0.2432 | 0.9957 | 1.0000 |
| H2O | mole frac. | 0.0255* | 0.0000 | 0.0000 | 0.0000 |

| Stream | | 100 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Vapour frac. | | 1.0000 | 1.0000 | 0.9966 | 0.0000 |
| Temperature | F | 70.0000* | 282.6442 | 100.0000* | 100.0000 |
| Pressure | psia | 14.7000* | 50.0000* | 45.0000 | 45.0000 |
| Molar Flow | MMSCFD | 4.0000* | 4.0000 | 4.0000 | 0.0134 |
| Methane | mole frac. | 0.5262* | 0.5262 | 0.5262 | 0.0000 |
| Nitrogen | mole frac. | 0.0097* | 0.0097 | 0.0097 | 0.0000 |
| CO2 | mole frac. | 0.4385* | 0.4385 | 0.4385 | 0.0001 |
| H2O | mole frac. | 0.0255* | 0.0255 | 0.0255 | 0.9999 |

| Stream | | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|
| Vapour frac. | | 1.0000 | 1.0000 | 0.9849 | 0.0000 |
| Temperature | F | 100.0000 | 323.0691 | 100.0000* | 100.0000 |
| Pressure | psia | 45.0000 | 155.0000* | 150.0000 | 150.0000 |
| Molar Flow | MMSCFD | 3.9866 | 3.9866 | 3.9866 | 0.0604 |
| Methane | mole frac. | 0.5280 | 0.5280 | 0.5280 | 0.0000 |
| Nitrogen | mole frac. | 0.0098 | 0.0098 | 0.0098 | 0.0000 |
| CO2 | mole frac. | 0.4400 | 0.4400 | 0.4400 | 0.0002 |
| H2O | mole frac. | 0.0222 | 0.0222 | 0.0222 | 0.9998 |

| Stream | | 10 | 11 | 12 | 101 |
|---|---|---|---|---|---|
| Vapour frac. | | 1.0000 | 1.0000 | 0.0000 | 1.0000 |
| Temperature | F | 100.0000 | 100.0000 | 100.0000 | 96.7213 |
| Pressure | psia | 150.0000 | 150.0000 | 150.0000 | 150.0000 |
| Molar Flow | MMSCFD | 3.9262 | 3.8979 | 0.0283 | 4.9363 |
| Methane | mole frac. | 0.5361 | 0.5400 | 0.0000 | 0.4596 |
| Nitrogen | mole frac. | 0.0099 | 0.0100 | 0.0000 | 0.0082 |
| CO2 | mole frac. | 0.4468 | 0.4500 | 0.0000 | 0.5322 |
| H2O | mole frac. | 0.0072 | 0.0000 | 1.0000 | 0.0000 |

Hyprotech's Process Simulator HYSIM - Licensed to Acrion Technologies Inc
Date 98/9/01 Version 386|C2.12 Case Name BOULI2.SIM
Time 10:24:15 Prop Pkg PRSV

LFG to Medium BTU Gas and Liquid CO2 Material Balance

| Stream | | 102 | 103 | 104 | 105 |
|---|---|---|---|---|---|
| Vapour frac. | | 1.0000 | 1.0000 | 1.0000 | 0.0000 |
| Temperature | F | 319.2572 | 100.0000* | 8.0000* | -13.4988 |
| Pressure | psia | 515.0000* | 510.0000 | 505.0000 | 505.0000 |
| Molar Flow | MMSCFD | 4.9363 | 4.9363 | 4.9363 | 0.7077 |
| Methane | mole frac. | 0.4596 | 0.4596 | 0.4596 | 0.0777 |
| Nitrogen | mole frac. | 0.0082 | 0.0082 | 0.0082 | 0.0007 |
| CO2 | mole frac. | 0.5322 | 0.5322 | 0.5322 | 0.9216 |
| H2O | mole frac. | 0.0000 | 0.0000 | 0.0000 | 0.0000 |

| Stream | | 106 | 107 | 108 | 109 |
|---|---|---|---|---|---|
| Vapour frac. | | 0.0000 | 1.0000 | 1.0000 | 1.0000 |
| Temperature | F | -14.6983 | -60.0009 | -26.2500* | -41.9207 |
| Pressure | psia | 500.5263 | 500.0000 | 495.0000 | 355.0000 |
| Molar Flow | MMSCFD | 1.3963 | 2.8322 | 2.8322 | 2.8322 |
| Methane | mole frac. | 0.0781 | 0.7431 | 0.7431 | 0.7431 |
| Nitrogen | mole frac. | 0.0007 | 0.0138 | 0.0138 | 0.0138 |
| CO2 | mole frac. | 0.9212 | 0.2432 | 0.2432 | 0.2432 |
| H2O | mole frac. | 0.0000 | 0.0000 | 0.0000 | 0.0000 |

| Stream | | 110 | 111 | 111a | 112 |
|---|---|---|---|---|---|
| Vapour frac. | | 1.0000 | 0.2170 | 0.8880* | 0.0000 |
| Temperature | F | 85.0000* | -53.5586 | -41.4277 | -41.4277 |
| Pressure | psia | 350.0000* | 160.0000* | 155.0000* | 155.0000 |
| Molar Flow | MMSCFD | 2.8322 | 0.7077 | 0.7077 | 0.0793 |
| Methane | mole frac. | 0.7431 | 0.0777 | 0.0777 | 0.0043 |
| Nitrogen | mole frac. | 0.0138 | 0.0007 | 0.0007 | 0.0000 |
| CO2 | mole frac. | 0.2432 | 0.9216 | 0.9216 | 0.9957 |
| H2O | mole frac. | 0.0000 | 0.0000 | 0.0000 | 0.0000 |

| Stream | | 113 | 114 | 114a | 115 |
|---|---|---|---|---|---|
| Vapour frac. | | 1.0000 | 1.0000* | 1.0000 | 1.0000 |
| Temperature | F | -41.4277 | -38.3558 | -67.2303 | 85.0000* |
| Pressure | psia | 155.0000 | 150.0000 | 25.0000* | 20.0000 |
| Molar Flow | MMSCFD | 0.6285 | 0.0793 | 0.0793 | 0.0793 |
| Methane | mole frac. | 0.0870 | 0.0043 | 0.0043 | 0.0043 |
| Nitrogen | mole frac. | 0.0008 | 0.0000 | 0.0000 | 0.0000 |
| CO2 | mole frac. | 0.9123 | 0.9957 | 0.9957 | 0.9957 |
| H2O | mole frac. | 0.0000 | 0.0000 | 0.0000 | 0.0000 |

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Date 98/9/01 Version 386|C2.12 Case Name BOULI2.SIM
Time 10:24:15 Prop Pkg PRSV

LFG to Medium BTU Gas and Liquid CO2 Material Balance

| Stream | | 116 | 117 | 118 | 120 |
|---|---|---|---|---|---|
| Vapour frac. | | 1.0000 | 0.0000 | 0.1330 | 0.0000* |
| Temperature | F | -45.9075 | -29.1241 | -67.0000* | -1.4316 |
| Pressure | psia | 180.0000 | 180.0000 | 78.2975 | 300.0000* |
| Molar Flow | MMSCFD | 0.4098 | 0.9865 | 0.9865 | 0.4828* |
| Methane | mole frac. | 0.2662 | 0.0000 | 0.0000 | 0.0000* |
| Nitrogen | mole frac. | 0.0023 | 0.0000 | 0.0000 | 0.0000* |
| CO2 | mole frac. | 0.7315 | 1.0000 | 1.0000 | 1.0000* |
| H2O | mole frac. | 0.0000 | 0.0000 | 0.0000 | 0.0000* |

| Stream | | 121 | 122 | 123 | 124 |
|---|---|---|---|---|---|
| Vapour frac. | | 0.1674 | 1.0000* | 1.0000 | 1.0000 |
| Temperature | F | -67.0000 | -66.9992 | 50.0000* | 296.4510 |
| Pressure | psia | 78.2975 | 78.2975 | 73.2975 | 315.0000* |
| Molar Flow | MMSCFD | 1.4693 | 1.4693 | 1.4693 | 1.4693 |
| Methane | mole frac. | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Nitrogen | mole frac. | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| CO2 | mole frac. | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| H2O | mole frac. | 0.0000 | 0.0000 | 0.0000 | 0.0000 |

| Stream | | 125 | 126 | 127 | 128 |
|---|---|---|---|---|---|
| Vapour frac. | | 1.0000 | 1.0000* | 0.0000* | 1.0000 |
| Temperature | F | 100.0000* | -0.4674 | -1.4325 | -45.0606 |
| Pressure | psia | 310.0000 | 305.0000 | 300.0000 | 155.0000 |
| Molar Flow | MMSCFD | 1.4693 | 1.4693 | 1.4693 | 1.0383 |
| Methane | mole frac. | 0.0000 | 0.0000 | 0.0000 | 0.1577 |
| Nitrogen | mole frac. | 0.0000 | 0.0000 | 0.0000 | 0.0014 |
| CO2 | mole frac. | 1.0000 | 1.0000 | 1.0000 | 0.8409 |
| H2O | mole frac. | 0.0000 | 0.0000 | 0.0000 | 0.0000 |

| Stream | | 129 | 129r |
|---|---|---|---|
| Vapour frac. | | 1.0000 | 1.0000 |
| Temperature | F | 85.0000* | 85.0000* |
| Pressure | psia | 150.0000 | 150.0000* |
| Molar Flow | MMSCFD | 1.0383 | 1.0383* |
| Methane | mole frac. | 0.1577 | 0.1577* |
| Nitrogen | mole frac. | 0.0014 | 0.0014* |
| CO2 | mole frac. | 0.8409 | 0.8409* |
| H2O | mole frac. | 0.0000 | 0.0000* |

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Date 98/9/01 Version 386|C2.12 Case Name BOULI2.SIM
Time 10:24:15 Prop Pkg PRSV

LFG to Medium BTU Gas and Liquid CO2 Material Balance

| | | | | | |
|---|---|---|---|---|---|
| Stream | | Wcomp1 | Wcomp2 | Wcomp3 | Wco2comp |
| Enthalpy | hp | 338.9172 | 358.1839 | 429.4122 | 141.3436 |
| Stream | | qair1 | Qair2 | qair3 | Qairco2 |
| Enthalpy | Btu/hr | 782829.1682 | 1.06754E+06 | 1.23710E+06 | 332170.3113 |
| Stream | | QHX1 | QCOND | QREB | QHX2 |
| Enthalpy | Btu/hr | 535902.3692 | 1.39351E+06 | 133786.1770 | 121706.9245 |
| Stream | | QHX3 | QHX4 | QHX5 | QHX6 |
| Enthalpy | Btu/hr | 380574.4022 | 54908.6695 | 11955.8772 | 917311.2946 |
| Stream | | QHx7 | QHX8 | QHX9 | QHX10 |
| Enthalpy | Btu/hr | 176751.6057 | 176748.1550 | 867367.1493 | 143935.1782 |
| Stream | | qdehi | Qhx12 | QRef-20 | |
| Enthalpy | Btu/hr | 56850.0206 | 342180.5610 | 2.07033E+06* | |

Hyprotech's Process Simulator HYSIM - Licensed to Acrion Technologies Inc
Date 98/9/01 Version 386|C2.12 Case Name BOULI2.SIM
Time 10:24:15 Prop Pkg PRSV Column Name ABSCO2

.LFG to Medium BTU Gas and Liquid CO2 Material Balance

**** Stage Variables ****

Reflux Ratio 0.75245

| Stg No | Press psia | Temp F | Flow Rates ( MMSCFD ) Liquid | Vapour | Feed | Draws | Duty MMBtu/hr |
|---|---|---|---|---|---|---|---|
| 1 | 500.0 | -60.0 | 2.1 | | | 2.8 V | -1.394 |
| 2 | 500.3 | -19.8 | 2.3 | 5.0 | | | |
| 3 | 500.5 | -14.7 | 1.0 | 5.2 | | 1.4 L | |
| 4 | 500.8 | -14.0 | 1.0 | 5.2 | | | |
| 5 | 501.1 | -13.9 | 1.0 | 5.2 | | | |
| 6 | 501.3 | -13.9 | 1.0 | 5.2 | | | |
| 7 | 501.6 | -13.8 | 1.0 | 5.2 | | | |
| 8 | 501.8 | -13.8 | 1.0 | 5.2 | | | |
| 9 | 502.1 | -13.8 | 1.0 | 5.2 | | | |
| 10 | 502.4 | -13.8 | 1.0 | 5.2 | | | |
| 11 | 502.6 | -13.7 | 1.0 | 5.2 | | | |
| 12 | 502.9 | -13.7 | 1.0 | 5.2 | | | |
| 13 | 503.2 | -13.7 | 1.0 | 5.2 | | | |
| 14 | 503.4 | -13.7 | 1.0 | 5.2 | | | |
| 15 | 503.7 | -13.6 | 1.0 | 5.2 | | | |
| 16 | 503.9 | -13.6 | 1.0 | 5.2 | | | |
| 17 | 504.2 | -13.6 | 1.0 | 5.2 | | | |
| 18 | 504.5 | -13.6 | 1.0 | 5.2 | | | |
| 19 | 504.7 | -13.5 | 1.0 | 5.2 | | | |
| 20 | 505.0 | -13.5 | | 5.2 | 4.9 | 0.7 L | |

Hyprotech's Process Simulator HYSIM - Licensed to Acrion Technologies Inc
Date 98/9/01 Version 386|C2.12 Case Name BOULI2.SIM
Time 10:24:15 Prop Pkg PRSV Column Name strip

LFG to Medium BTU Gas and Liquid CO2 Material Balance

**** Stage Variables ****

| Stg No | Press psia | Temp F | Flow Rates ( MMSCFD ) Liquid | Vapour | Feed | Draws | Duty MMBtu/hr |
|---|---|---|---|---|---|---|---|
| 1 | 180.0 | -45.9 | 1.1 | | 1.4 | 0.4 V | |
| 2 | 180.0 | -36.3 | 1.2 | 0.1 | | | |
| 3 | 180.0 | -31.8 | 1.2 | 0.2 | | | |
| 4 | 180.0 | -30.1 | 1.2 | 0.2 | | | |
| 5 | 180.0 | -29.4 | 1.2 | 0.2 | | | |
| 6 | 180.0 | -29.2 | 1.2 | 0.2 | | | |
| 7 | 180.0 | -29.2 | 1.2 | 0.2 | | | |
| 8 | 180.0 | -29.1 | 1.2 | 0.2 | | | |
| 9 | 180.0 | -29.1 | 1.2 | 0.2 | | | |
| 10 | 180.0 | -29.1 | | 0.2 | | 1.0 L | 0.134 |

# APPENDIX B

## USIJI Proposal Outline

I. **Participants in the Project**
   A. U.S.
      1. Acrion International, Inc.
      2. Acrion Technologies, Inc.
      Power Management Corporation
      Crestmont Capital Projects, Inc.
      EMCON, Inc.
   B. Non U.S.
      1. Government of Romania
      2. City of Popesti-Leordeni
      3. City of Bucharest
      4. Petrodesign S.A.

II. **Project Information**
   A. Description and Milestones
      1. Brief summary of project
      2. Precise location of project
      3. Sources and sinks of greenhouse gas emissions associated with project
      4. Specific measures to reduce or sequester greenhouse gas emissions (items 1-4 excerpted from Final Report)
      5. Dates of significant milestones (to be determined)
   B. Sources of Funding for Specific Measures to Reduce GHG Emissions
   C. Assignment of Emissions Reductions
   D. Additionality (from PMC proposal to Popesti)
   E. Acceptance by the National or Federal Government of Host Country (letter signed by Mr. Janos Botond Kiss, State Secretary, Ministry of Waters, Forests and Environmental Protection, GOR, page B-2)
   F. Technical Assistance (by EMCON and Acrion)

III. **Greenhouse Gas Emissions and Sequestration (Section 4, Final Report)**
   A. Baseline Estimates of Emissions and/or Sequestration of Greenhouse Gases Without Measures
   B. Estimate of Emissions and Sequestration of Greenhouse Gases With Measures
   C. Monitoring Greenhouse Gas Emissions and Updating Emissions Estimates
   D. External Verification
   A. Nongreenhouse Gas Environmental Impacts of Project (PMC Popesti Proposal)
   B. Development Impacts of Project (enhancements of local economy)
   C. Efforts to Reduce Domestic Greenhouse Gas Emissions by U.S. Participants
   D. Other Information for Consideration by Panel

V. **Required Certification**

MINISTRY OF WATERS, FORESTS AND ENVIRONMENTAL PROTECTION

State Secretary Cabinet

**To:** **Mr. Ward Sanders**
**Power Management Corporation**
fax: 001 425 451 9637

Dear Mr. Sanders,

Related to your letter dated 5.03.1998, I would like to inform you that our answer was submitted on 12.03.1998 to PETRODESIGN SA, with the following topic:

*1. The project concerning the decrease of the biogas dispersed into the air at Ochiul Boului Landfill, by solving the aspect of its collection and use for the generation of electric power, represents a punctiform target of great importance.*

*2. The project on Ochiul Boului will be a demonstrative pilot project with possibilities to apply it in other similar zones, too.*

*3. The Minister of Water, Forests and Environmental Protection generally agrees with all the projects improving the environmental conditions and particularly those related to wastes.*

Sincerely yours,

Janos Botond KISS
State Secretary

Cc: Mr. Ioan Botgros, Director PETRODESIGN, fax: 3123005